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GUIDEBOOK TO THE HAWAIIAN PLANETOLOGY CONFERENCE

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PREFACE

Planetology is a multidisciplinary field involving geologists, chemists, astronomers, meteorologists, physicists, engineers, and others. While planetologists surely cannot be specialists in all areas of their field, they must at least be aware of the most important aspects of the allied sciences.

Among these aspects is volcanism, whose significance among the geologic processes is only now being fully realized in the light of more comprehensive data from Earth explorations as well as missions to the terrestrial planets. The Hawaiian Planetology Conference to be held in October 1974 was organized to provide planetologists with practical experience in volcanic geology and the opportunity to establish communications with volcanologists in an era when opportunities for study in true comparative planetary geology are beginning to unfold.

Many people contributed a great deal of time and effort to produce this guidebook. I thank first and foremost the contributors, most of whom worked under very difficult time restrictions in order to have the guide printed in time for the conference. I am particularly grateful to Don Peterson and the staff of the U.S. Geological Survey-Hawaiian Volcano Observatory (HVO) for co-hosting the conference and for assisting with the field trips. Special thanks go to Robin Holcomb (HVO) who spent long and diligent hours to provide many of the photographs for the guide.

I thank Professor Abbott for giving free access to his outstanding collection of photographs on Hawaiian geology, many of which are included here.

Some of the aerial photographs were obtained during flights with Tom Lodge, Hilo, at various times 1970-1974, and I wish to thank him for his special efforts in accommodating the needs of "geological photography." I also thank Jack Lockwood, HVO staff, for a much needed flight and photographic mission in June 1974.

I thank D. Swanson, W. Duffield, and J. King for reviewing some of the chapters, and G. A. Macdonald for leading some of the field trips.

The production of this guidebook has been greatly facilitated by the staff of NASA-Ames Research Center. I particularly thank Sarah Ogata, Publications Office, and Darryll Stroud, Graphics Branch.

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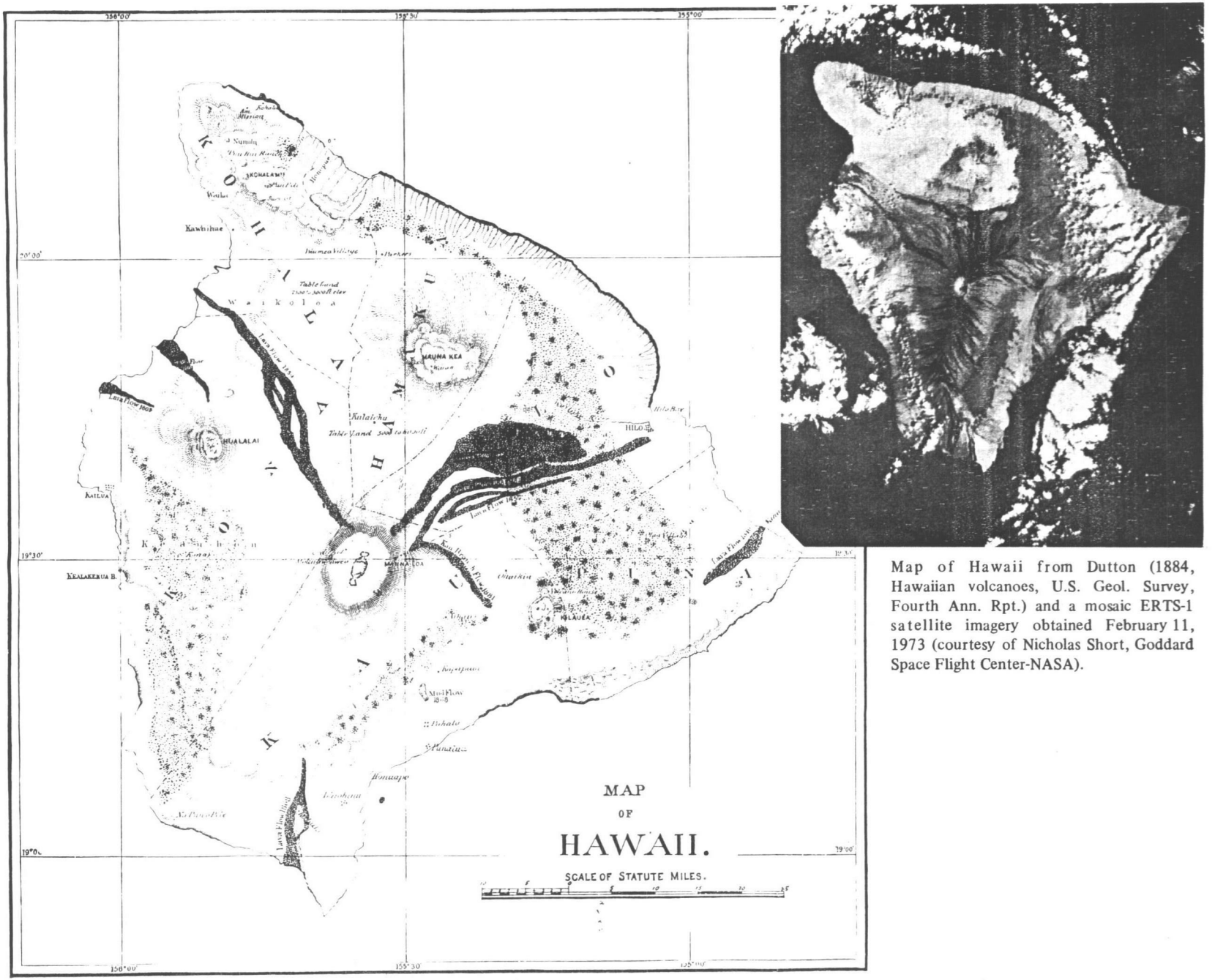
R. Greeley, 1974



Map of Hawaii from Dutton (1884, Hawaiian volcanoes, U.S. Geol. Survey, Fourth Ann. Rpt.) and a mosaic ERTS-1 satellite imagery obtained February 11, 1973 (courtesy of Nicholas Short, Goddard Space Flight Center-NASA).

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INTRODUCTION

Although the role of volcanism in the geology of Earth has long been recognized, its full significance among the geologic processes was not realized until data gathered for the ocean basins revealed extensive basaltic lava flows. The occurrence and effects of volcanism on other planets is also beginning to emerge. Data from unmanned lunar missions, returned samples, photographs, and astronaut observations indicate that volcanism played a significant role in shaping the lunar surface. Mariner missions to Mars have shown that volcanic processes dominate several regions of Mars, evidenced by tremendous shield volcanoes, dome volcanoes, flood-type lava flows, and fissures. Recent Mariner 10 imagery for Mercury also shows flow-like features of probable volcanic origin.

With geological data available for all inner planets except Venus, we are entering an era of true *comparative* planetary geology, when knowledge of the differences and similarities for classes of structures (e.g., shield volcanoes) will lead to a better understanding of general geological processes, regardless of planet. Thus, it is imperative that planetologists, particularly those involved in geological mapping and surface feature analysis for terrestrial planets, be familiar with volcanic terrain in terms of its origin, structure, and morphology. One means of gaining this experience is through field trips in volcanic terrains – hence, the Hawaiian Planetology Conference. In addition, discussions with volcanologists at the conference will provide an important basis for establishing communications between the two fields that will facilitate comparative studies as more data become available.

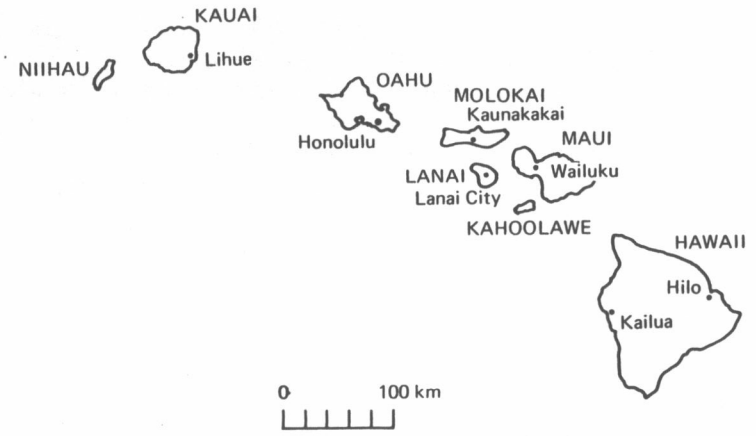


Fig. 1-1

THE CONFERENCE SITE

Hawaii (Fig. 1-1) was selected as the site for the planetology conference for several reasons:

1. The best terrestrial counterparts for the dominant martian volcanic landforms are found in Hawaii.
2. There is a wide variety of fresh volcanic landforms available for comparisons with extraterrestrial features, and the field areas are relatively accessible.
3. The conference could draw on the expertise of volcanologists of the University of Hawaii and from the Hawaiian Volcano Observatory of the U.S. Geological Survey.
4. There is an excellent possibility of observing active volcanic eruptions.

Mauna Ulu ("growing mountain") is the new Hawaiian shield volcano that has been growing through almost constant eruptive activity since its birth in 1969. It has provided the unique opportunity to observe the extremely complex and multitudinous stages of early shield growth (see Chapter 5). In the short period of five years, the summit region of Mauna Ulu has passed through many complex morphologies, involving multiple craters, single craters, perched lava lakes, steep-sided cone phases, etc. Each phase has left its imprint on the stratigraphy and morphology of the volcano. Such extensive and complex activity in so brief a period points up the fallacy of the oversimplifications so often found in studies of prehistoric volcanoes; it also demonstrates the potential difficulty of interpreting extraterrestrial volcanic regions.

GUIDEBOOK ORGANIZATION

This guidebook was prepared both for the participant who is new to Hawaii and for those who are familiar with the Islands. Because the culture of Hawaii is unique among the 50 states, some sections are included here that might not normally be found in a guidebook of this type. Part I covers the historical, geographical, and regional geologic settings for the conference, and includes a general introduction to volcanic stratigraphy, a photographic essay describing various landforms observed during eruptive activity at Kilauea Volcano, and a general discussion of the geology of the island of Hawaii.

Part II includes the field trips, which fall into two categories: (1) formal trips scheduled as part of the conference and including group transportation and leadership; and (2) informal, or self-guided trips, not scheduled during the conference, which can be organized by participants who must make their own travel arrangements.

HAWAIIAN PLACE NAMES AND GEOGRAPHIC FEATURES

Many Hawaiian words seem quite formidable, particularly their pronunciation. The Hawaiian alphabet consists of 12 letters – five vowels and seven consonants. Pronunciation is easier if one remembers to sound each vowel separately. The vowels are sounded:

a	"ah"	as in father
e	"eh"	as in feather
i	"ee"	as in eat
o	"oh"	as in note
u	"oo"	as in true

The seven consonants (*h, k, l, m, n, p,* and *w*) are pronounced as in English, except that occasionally *w* is sounded as *v*. In addition, some words are pronounced with glottel stops, shown by a reversed apostrophe (ʻ), such as Kaʻu. It is similar to the stopping sound between the ohs in English oh-oh! The macrons, $\bar{a}, \bar{e}, \bar{i}, \bar{o}, \bar{u}$, denote long, stressed vowels. The eight vowel pairs, *ae, ai, ao, au, ei, eu, oi, ou,* are linked together so that they merge to one smooth sound with the emphasis placed on the first vowel. Good luck!

ʻAlae	mudhen
Aloʻi	mud puddle, pool
Halemaʻumaʻu	fern house
Hamakua	long corner
Hapuna	spring
Hawaiʻi	(meaning lost)
Hawi	a time of famine*
Heiau	(ancient religious enclosure)
Hilina	struck
Hilo	(first night of the new moon)
Hoʻokena	to satisfy thirst
Hualalai	obstructing the flow*
Kailua	two seas
Kalapana	announce noted place
Kamuela	Samuel
Kapoho	the hollow
Kaʻu	the breast
Kaumana	the miraculous expression*
Kilauea	spewing, much spreading
Kilauea Iki	little Kilauea
Kohala	pandanus drawn*
Kolekole	raw
Kona	leeward
Kulani	like heaven
Laupahoehoe	smooth lava flat
Lua	pit, crater
Lua Manu	bird crater

Makaopuhi	eel's eye
Mauna	mountain
Mauna Kea	white mountain
Mauna Loa	long mountain
Mauna Ulu	growing mountain
Miloli'i	little milo tree
Moku'aweoweo	red section
Na'alehu	volcanic ashes
Naniloa	most beautiful
Napau	the endings
Ninole	bending
Pahala	cultivation by burning mulch
Pahoa	dagger
Pana'ewa	crooked shooting
Papa'aloa	much burned
Papa'ikou	kou tree hut
Pauahi	consumed by fire
Puna	coral, lime*
Punalu'u	spring dived for
Puu	hill
Puu huhuhulu	shaggy hill
Puu uloa	long hill
Waiakea	broad waters
Waikoloa	duck water
Wailoa	long water
Wailuku	water of destruction
Waimea	reddish water
Waiohinu	shiny water
Waipi'o	curved water

*Not a direct translation.

GLOSSARY OF SELECTED VOLCANIC TERMS

The following glossary of selected volcanic terms is included primarily as an aid to those who are unfamiliar with volcanology. Other participants, however, may be interested in the photographs that accompany some of the descriptions; many of the photographic examples are from Hawaii.

Most of the definitions are from the American Geological Institute glossary (Gary *et al.*, 1972) with minor changes and additions. Other standard references are Macdonald (1972, 1967), Wentworth and Macdonald (1953), and Green and Short (1971).

accretionary lava ball. A rounded mass, varying in size from a few centimeters to several meters, formed on the surface of a lava flow such as aa by the molding of viscous lava around a core of already solidified lava (Fig. 10-11) (Gary *et al.*, 1972).

agglutinate n. A deposit of flattened bombs and spatter that were still sufficiently hot to weld together (Wentworth and Macdonald, 1953). Also spelled: agglutinite.

ash [volc]. Fine pyroclastic material (under 2.0 mm diameter (Macdonald, 1972)). The term usually refers to the unconsolidated material but is sometimes also used for its consolidated counterpart, or *tuff.* Syn: *dust; volcanic ash; volcanic dust* (Gary *et al.*, 1972).

blister [volc]. A surficial swelling of the crust of a lava flow formed by the puffing up of gas or vapor beneath the flow. A blister is usually about one meter in diameter, and is hollow. Cf: *tumulus* (Gary *et al.*, 1972).

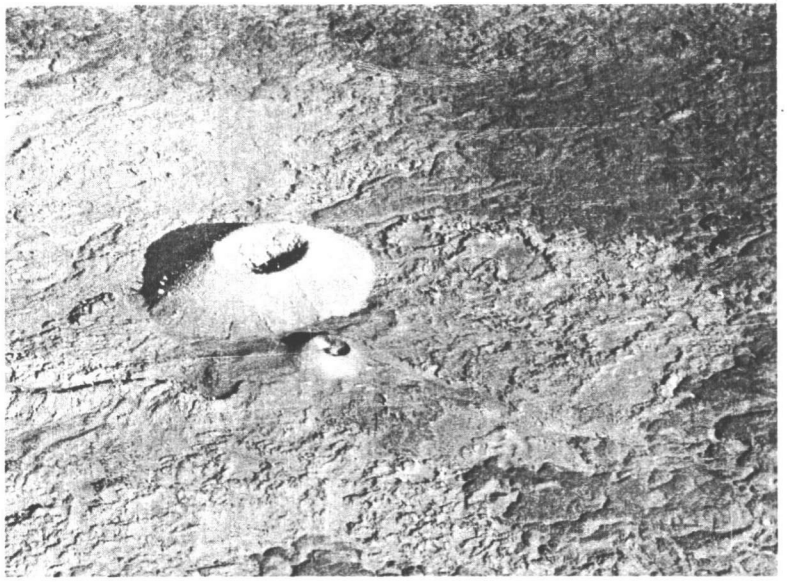
block. A pyroclast that was ejected in a solid state: it is in the size range of about 5 cm in diameter to several cubic meters. It may be essential, accessory, or accidental. Cf: *lapilli; volcanic gravel; cinder* (Gary *et al.*, 1972).

bomb. A pyroclast that was ejected while viscous and received its rounded shape while in flight. It is larger than lapilli in size, and may be vesicular to hollow inside. Actual shape or form varies greatly, and is used in descriptive classification of bombs, e.g., rotational bomb; spindle bomb (Gary *et al.*, 1972).

caldera. A large, basin-shaped volcanic depression, more or less circular or cirquelike in form, the diameter of which is many times greater than that of the included vent or vents, no matter what the steepness of the walls or form of the floor (Gary *et al.*, 1972). Can result from collapse, explosion, erosion, or a combination of these processes.

cinder. An uncemented, juvenile, vitric, and vesicular pyroclastic fragment that has been given various size classifications: 4-32 mm diameter; 0.5-5.0 cm diameter; so fine that its nature is not discernible to the naked eye; equivalent to the size of *lapilli* but vesicular; or, the same as scoria. Cf: *block* (Volc.); *volcanic gravel* (Gary *et al.*, 1972).

cinder cone. A conical hill formed by the accumulation of cinders and other scoriaceous ejecta, normally of basaltic or andesitic composition. The steepness of the slopes may differ widely depending on the coarseness of the ejecta, the height of eruption, wind velocity, and other factors, but is normally steeper than 10 degrees (Gary *et al.*, 1972).



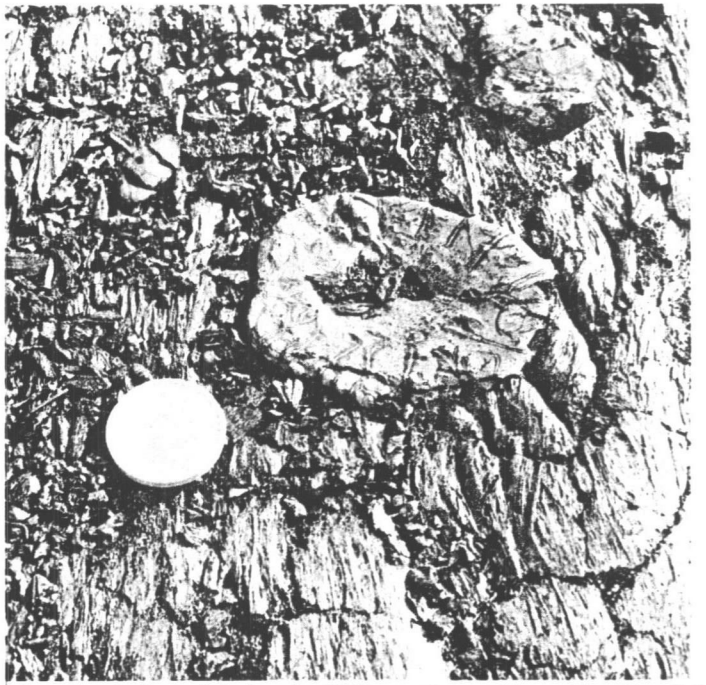
Small cinder cones on the Ka'u Desert. (U.S.G.S.-Hawaiian Volcano Observatory photograph by John Lockwood, June 1974).

columnar jointing. Parallel, prismatic columns, either hexagonal or pentagonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks. It is formed as the result of contraction during cooling. Syn: *columnar structure; prismatic jointing; prismatic structure* (Gary *et al.*, 1972).

corded pahoehoe. The typical kind of pahoehoe, having a surface resembling coils of rope. Cf: *elephant-hide pahoehoe; entrail pahoehoe; festooned pahoehoe; filamented pahoehoe; sharkskin pahoehoe; shelly pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

cored bomb. A type of volcanic bomb that has a core of nonvolcanic rock or already solidified lava, around which the lava has molded itself. Syn: *perelith* (Gary *et al.*, 1972).

cow-dung bomb. A type of volcanic bomb whose flattened shape is due to its impact while still viscous (Gary *et al.*, 1972).



Cow-dung bomb, formed during the 1974 eruptions at Mauna Ulu, Hawaii. Lens cap to the lower left of bomb is 6.5 cm in diameter. (Photograph by Ronald Greeley, University of Santa Clara, April 1974.)

driblet adj. A syn. of *spatter.*

driblet cone. *hornito.*

driblet spire. *hornito.*

elephant-hide pahoehoe. A type of pahoehoe having a wrinkled and draped surface. Cf: *corded pahoehoe; entrail pahoehoe; festooned pahoehoe; filamented pahoehoe; sharkskin pahoehoe; shelly pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

entrail pahoehoe. A type of pahoehoe that has a surface resembling an intertwined mass of entrails, formed on steep slopes as dribbles around and through cracks in the flow crust. Cf: *corded pahoehoe; elephant-hide pahoehoe; festooned pahoehoe; filamented pahoehoe; sharkskin pahoehoe; shelly pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

explosion breccia. A type of volcanic breccia that is formed by a volcanic explosion. Syn: *eruption breccia; pyroclastic breccia* (Gary *et al.*, 1972).

festooned pahoehoe. A type of pahoehoe, the ropy surface of which has been dragged by flow of underlying molten lava into festoon patterns. Cf: *corded pahoehoe; elephant-skin pahoehoe; entrail pahoehoe; filamented pahoehoe; sharkskin pahoehoe; shelly pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

filamented pahoehoe. A type of pahoehoe, the surface of which displays threadlike strands formed by escaping gas bubbles, and that are recumbent and aligned with the direction of flow. It is a common type and is often found superimposed on other forms (Gary *et al.*, 1972).

fissure A surface of fracture or a crack in rock along which there is a distinct separation (Gary *et al.*, 1972).

fissure volcano. One of a series in a pattern of eruption that is along a fissure plane as a series of vents; such a flow characteristically forms as extensive sheets (Gary *et al.*, 1972).

Oblique aerial view of the Great Crack on the Ka'u Desert. Vents along this fissure produced extremely fluid lavas in 1823. Photograph by Ronald Greeley, University of Santa Clara, June 1974.

flood basalt. *plateau basalt.*

flow unit. A successive but essentially contemporaneous layer or portion constituting a single larger flow. Each flow unit represents a separate gush or sheet of liquid lava pouring over one another during the course of a single eruption (Macdonald, 1967).

grooved lava. Grooves and striations that are produced when semisolid but still-plastic lava moves past an irregular surface (Macdonald, 1967).

hornito. A *spatter cone*, esp. around a rootless vent on a lava flow. Syn: *driblet cone* (Gary *et al.*, 1972).

lapilli. Pyroclastics that may be either essential, accessory, or accidental in origin, of a size range that has been variously defined within the limits of 1-64 mm diameter. The fragments may be either solidified or still viscous when they land (though some classifications restrict the term to the former); thus there is no characteristic shape. An individual fragment is called a *lapillus.* Cf: *volcanic gravel; block* [volc] ; *cinder* (Gary *et al.*, 1972).

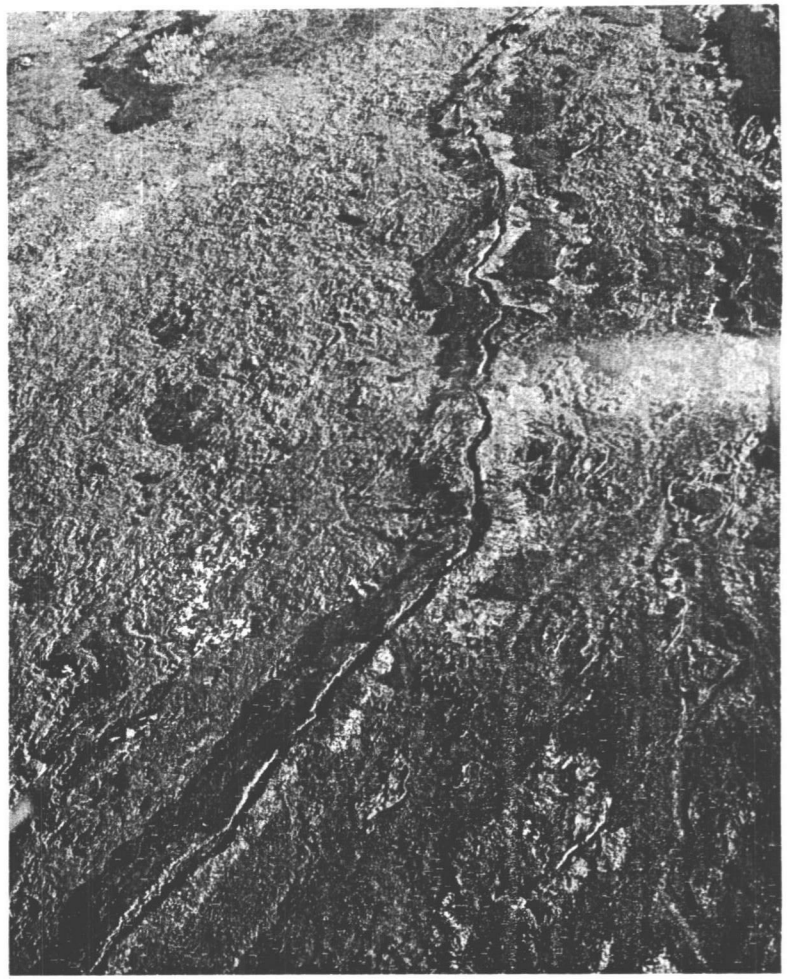
lapilli tuff. An indurated deposit that is predominantly lapilli, with a matrix of tuff (Gary *et al.*, 1972).

lava. A general term for a molten extrusive; also, for the rock that is solidified from it (Gary *et al.*, 1972).

lava ball. A globular mass of lava that is scoriaceous inside and compact on the outside; it is formed by the coating of a fragment of scoria by fluid lava. Syn: *pseudobomb; volcanic ball; volcanic dumping.* (Gary *et al.*, 1972).

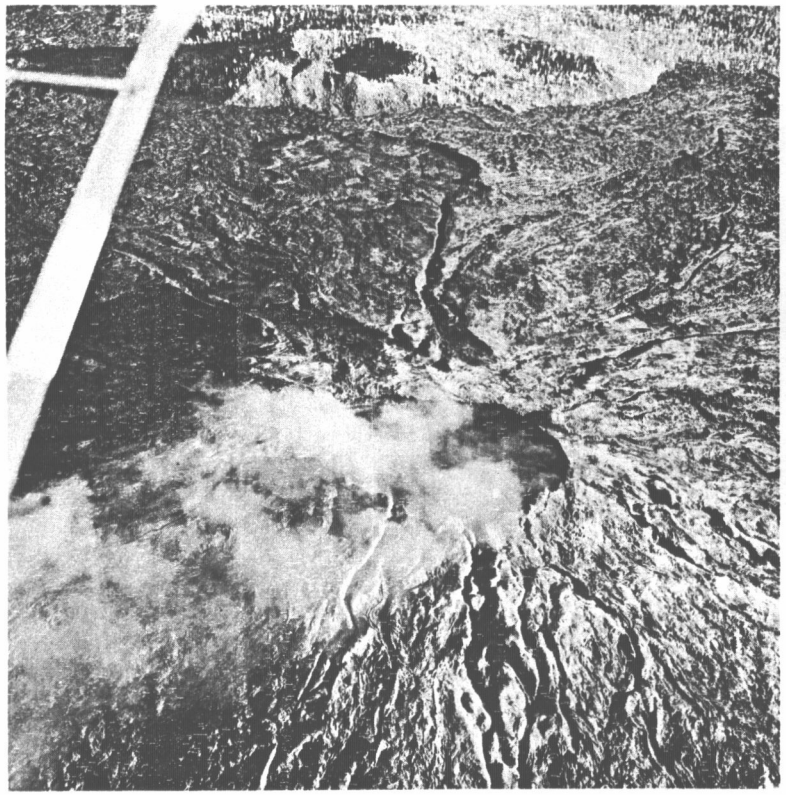
lava breccia. *volcanic breccia.*

lava channel. A linear depression that forms in lava flows and carries lava to the flow front.



Oblique aerial view of a lava channel that developed in pahoehoe flows from Mauna Ulu, Hawaii. Note the lava levees that form a broad arch along the axis of the channel. Photograph by Ronald Greeley, University of Santa Clara, June, 1974.

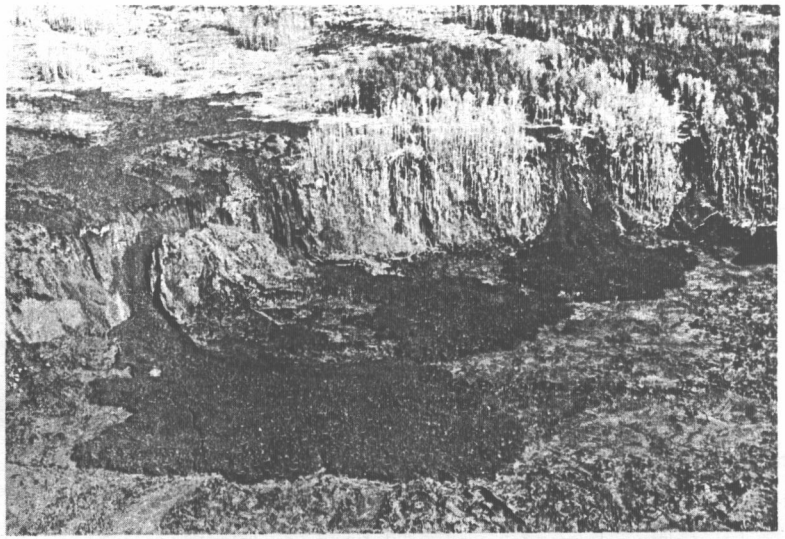
lava cone. Miniature shield volcanoes composed largely of lava flows with very little pyroclastic material, such as Mauna Iki on the Ka'u Desert, Hawaii (Wentworth and Macdonald, 1953).



Oblique aerial view of the lava cone of Mauna Ulu in June 1974. Note the numerous lava channels that are radial to the summit crater. Fume is emanating from an active lava lake contained in the summit crater. Puu Huluhulu, a small cinder-spatter cone, is near the top of the picture. Photograph by Ronald Greeley, University of Santa Clara, June 1974.

lava dome. (a) A dome-shaped mountain of solidified lava in the form of many individual flows, formed by the extrusion of highly viscous lava. Cf: *volcanic dome.* (b) A tumulus developed on a lava flow (Gary *et al.*, 1972).

lava fan. Subaerial deposit of lava resembling an alluvial fan; may form when lava flows spill over steep cliffs then spread laterally at the base of the cliff.

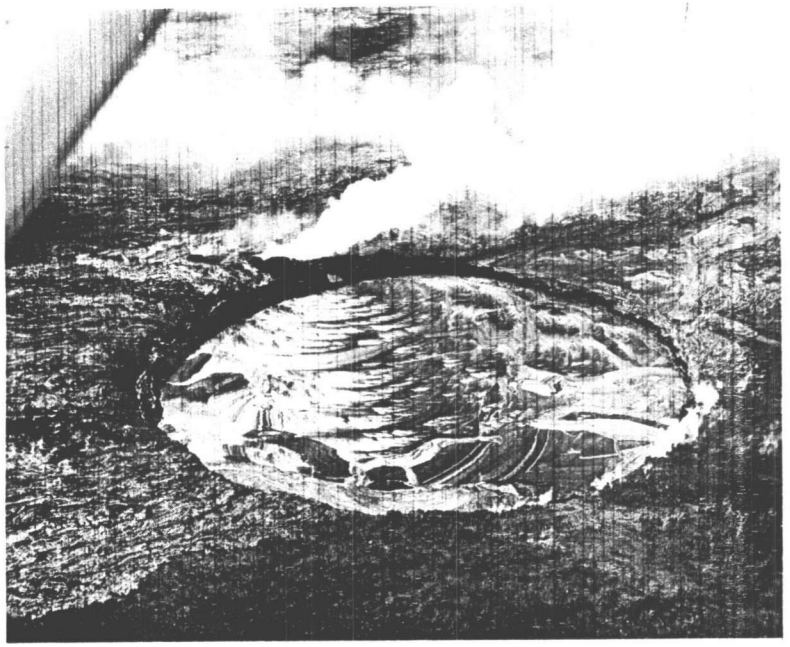


Lava fans on the northwest rim of Napau Crater when the 1969 lava flows from Mauna Ulu spilled over the crater rim. NASA-Ames photograph by Ronald Greeley, 1970.

lava flow. A lateral, surficial outpouring of molten lava from a vent or a fissure; also, the solidified body of rock that is so formed. Syn: *flow* [volc]; *nappe* [volc] (Gary *et al.*, 1972).

lava lake. A lake of usually basaltic molten lava in a volcanic crater or depression. The term refers to solidified and partly solidified stages as well as to the molten, active lava lake (Gary *et al.*, 1972).

lava levee. The scoriaceous sheets of lava that overflowed their natural channels of flow and solidified to form a levee, similar to a levee formed by an overflowing stream of water (Gary *et al.*, 1972).



Active lava lake within a pit crater, Chain of Craters, east rift zone of Kilauea Volcano. U.S.G.S.-Hawaiian Volcano Observatory photography by R. T. Okamura, 1965.

lava ring. Wall of spatter built up around an active lava lake by the ejecta from many small lava fountains (Wentworth and Macdonald, 1953).

lava toe. One of a series of small, bulbous projections that develop at the front of a moving pahoehoe flow, formed by the breaking open of the crust and the emergence of fluid lava. Syn: *toe* (Gary *et al.*, 1972).

lava tree. A *lava tree mold* that projects above the surface. Syn: *lava tree cast* (Gary *et al.*, 1972).

Lava trees along Chain of Crater Road. Photograph by W. Hartman, Planetary Science Institute Associates, Tucson, Arizona, 1965.

lava tree mold. A cylindrical hollow in a lava flow formed by the envelopment of a tree by the flow, solidification of the lava in contact with the tree, and disappearance of the tree by burning and subsequent removal of the charcoal and ash. The inside of the mold preserves the surficial features of the tree. See also: *lava tree* (Gary *et al.*, 1972).

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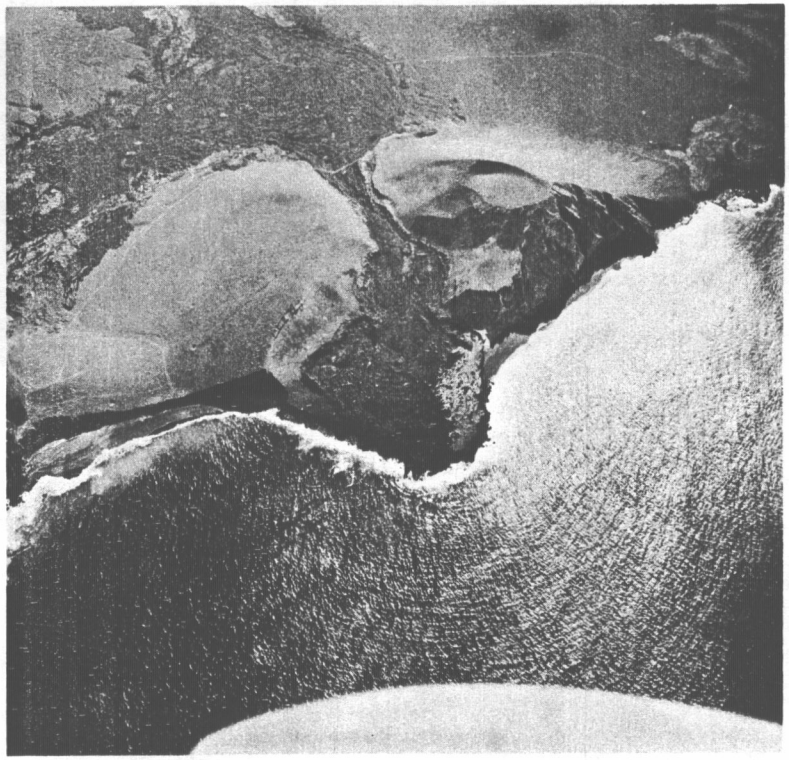
lava trench. A collapsed *lava tube* (Gary *et al.*, 1972).

Lava trench formed by the collapse of a lava tube in the Snake River Plains, Idaho. Jeep trail indicates scale; illumination from the right. NASA-Ames Photograph by Ronald Greeley, 1969.

lava tube. A hollow space beneath the surface of a solidified lava flow, formed by the withdrawal of molten lava after the formation of the surficial crust. See also: *lava trench; volcanic flow drain.* Syn: *lava tunnel* (Gary *et al.*, 1972).

lava tunnel. *lava tube.*

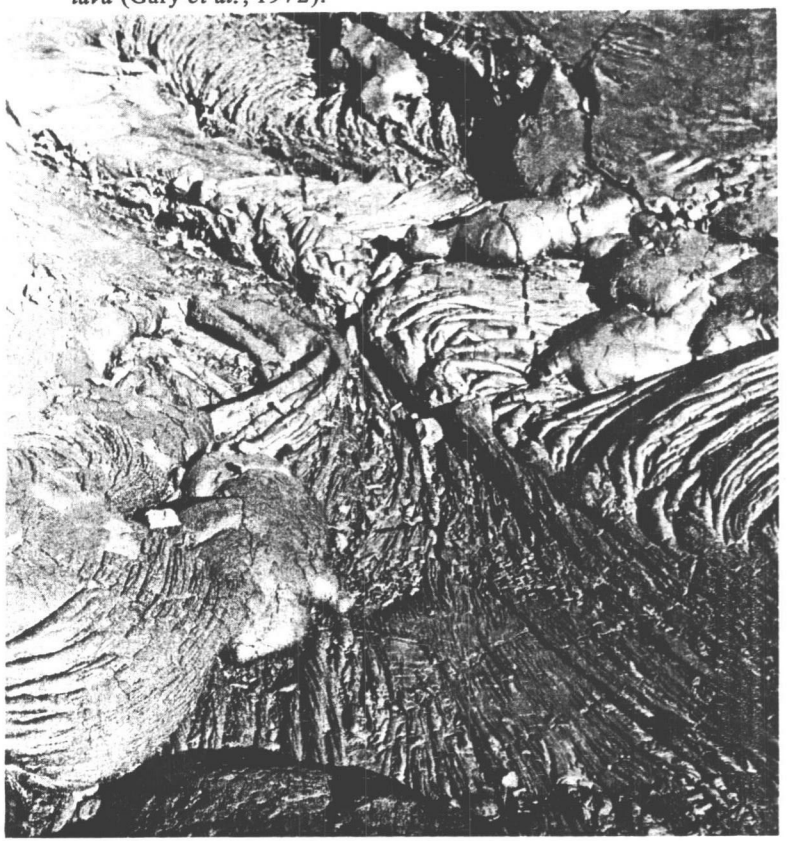
littoral cone. A small volcanic cone of a rootless vent, formed where a lava flow enters a body of water (Gary *et al.*, 1972).



Littoral cone (Puu Hou), formed when a historic flow from Mauna Ulu entered the sea. Photograph by Ronald Greeley, University of Santa Clara, June 1974.

littoral explosion. An explosion that is the result of the contact of a flow of molten lava at the edge of a body of water; a *hydroexplosion* (Gary *et al.*, 1972).

pahoehoe. A type of lava flow having a glassy, smooth, and billowy or undulating surface; it is characteristic of Hawaii. It tends to be a basaltic, glassy, and porous type of lava. Cf: *aa.* Pron: pa-ho-e-ho-e. Etymol: Hawaiian. Obs. syn. *dermolith.* Syn: *ropy lava* (Gary *et al.*, 1972).



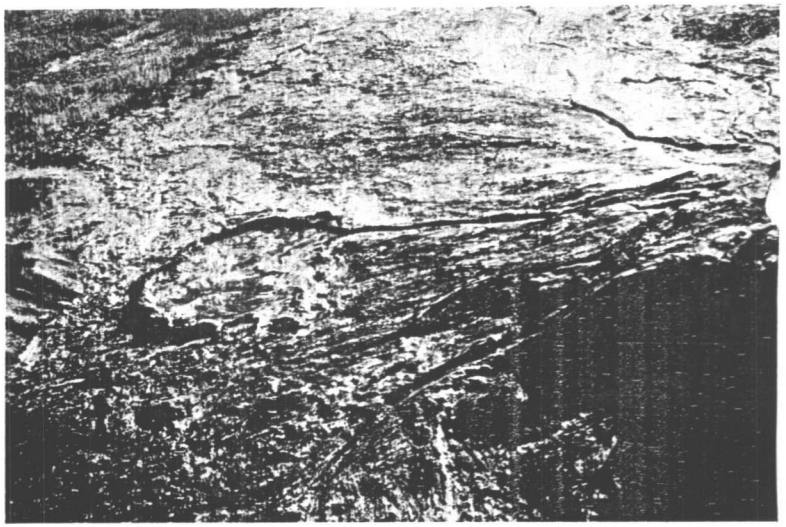
Pahoehoe lava. Photograph by Dale P. Cruikshank, University of Hawaii.

palagonite. An altered tachylite, brown to yellow or orange and found in pillow lavas as interstitial material or amygdules (Gary *et al.*, 1972).

Pele's hair. A naturally formed spun glass formed by blowing out during quiet fountaining of fluid lava, sometimes in association with *Pele's tears.* Its diameter is less than half a millimeter, but it can be as long as two meters in length. Etymol: Pele, Hawaiian goddess of fire. Syn: *lauoho o pele; filiform lapilli; capillary ejecta* (Gary *et al.*, 1972).

Pele's tears [pyroclast]. Small, solidified drops of volcanic glass behind which trail pendants of *Pele's hair.* They may be tear-shaped, spherical, or nearly cylindrical. Etymol: Pele, Hawaiian goddess of fire. Cf: *tear-shaped bomb* (Gary *et al.*, 1972).

perched lava pond. A small lava lake contained by lava levees and resulting from relatively low eruptive rates (see Chapter 5).



Small perched lava pond (center) on the flank of Mauna Ulu (summit crater on the right). Photograph by Ronald Greeley, University of Santa Clara, June 1974.

pillow lava. A general term for those lavas displaying *pillow structure* and considered to have formed in a subaqueous environment; such a lava is usually basaltic or andesitic, esp. a spilite. Syn: *ellipsoidal lava* (Gary *et al.*, 1972).

pit crater. Circular or ellipsoidal depressions resulting from collapse; the pit is sunk below the gently sloping surface of the volcano (Wentworth and Macdonald, 1953).

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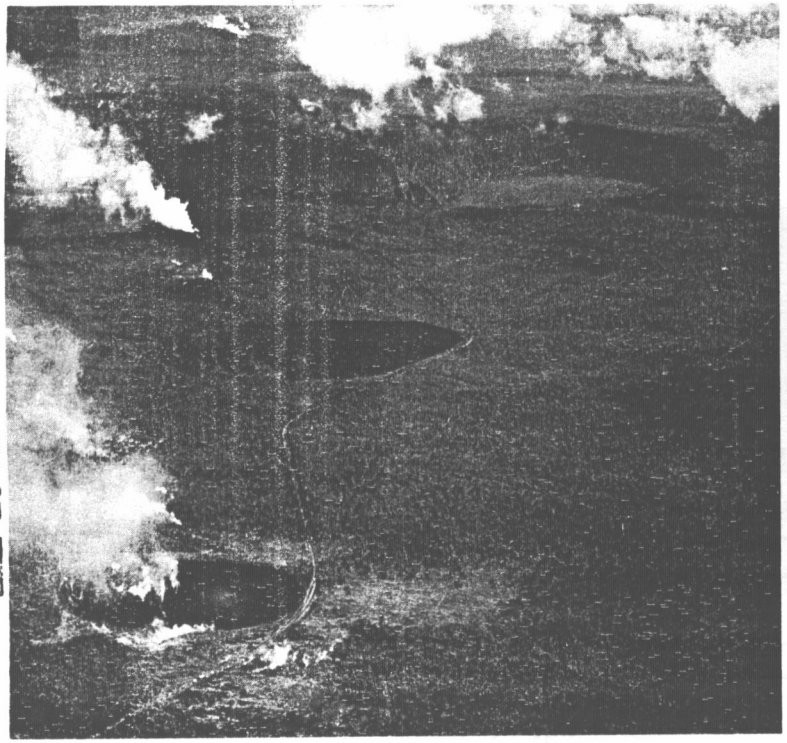


Oblique aerial view of pit craters Aloi (foreground) and Alae (middle) before their burial by lavas from Mauna Ulu, east rift zone of Kilauea Volcano. Photograph by D. L. Hamilton, National Park Service, December 9, 1962.

plateau basalt. An extensive, thick and smooth basaltic lava flow or successive flows of high-temperature, fluid basalt from fissure eruptions, accumulating to form a plateau, e.g., the Columbia-Snake Plateau of the northwestern U.S. Cf: *shield basalt.* Syn: *flood basalt* (Gary *et al.*, 1972).

pressure plateau. An uplifted area of a thick, ponded lava flow, measuring up to three or four meters, the uplift of which is due to the intrusion of new lava from below that does not reach the surface. The lower part of such a flow may remain fluid for weeks (Gary *et al.*, 1972).

pressure ridge [volc]. An elongate uplift of the congealing crust of a lava flow, probably due to the pressure of the underlying and still flowing lava (Gary *et al.*, 1972).

reticulite. Thread-lace scoria (Gary *et al.*, 1972).

rift. A narrow cleft, fissure, or other opening in rock (as in limestone), made by cracking or splitting (Gary *et al.*, 1972).

rift zone. (a) A system of crustal fractures; a *rift* [struc geol]. (b) in Hawaii, a zone of volcanic features associated with underlying dike complexes. Syn: *volcanic rift zone.*

rootless vent. A source of lava that is not directly connected to a volcanic vent or magma source; it may be an accumulation of overflow or an outflow from an otherwise solidified lava flow (Gary *et al.*, 1972).

sharkskin pahoehoe. A type of pahoehoe, the surface of which displays innumerable tiny spicules or spines produced by escaping gas bubbles. Cf: *corded pahoehoe; elephant-hide pahoehoe; entrail pahoehoe; festooned pahoehoe; filamented pahoehoe; shelly pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

shark-tooth projection. A structure formed by the pulling or tearing apart of plastic lava into fine, sharp points several centimeters in length. Such projections may occur along the edge of a flow or along a slump scarp (Gary *et al.*, 1972).

shelly pahoehoe. A type of pahoehoe, the surface of which contains open tubes and blisters; its crust is 1-30 cm thick. Cf: *corded pahoehoe; elephant-hide pahoehoe; entrail pahoehoe; festooned pahoehoe; filamented pahoehoe; sharkskin pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

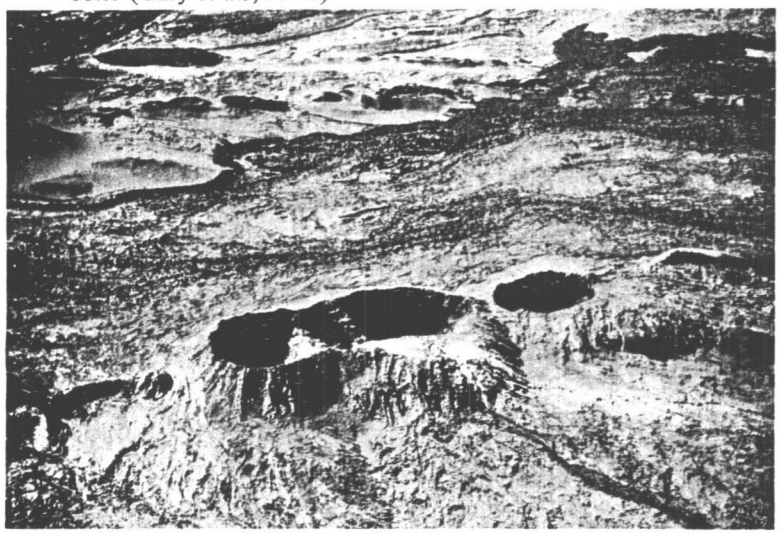
shield basalt. A basaltic lava flow that erupted from numerous, small and closely spaced shield-volcano vents and that coalesced to form a single unit. It is generally of smaller extent than a *plateau basalt* (Gary *et al.*, 1972).

slab pahoehoe. A type of pahoehoe, the surface of which consists of a jumbled arrangement of plates or slabs of flow crust, presumably so arranged due to the draining away of the bubbles, and that are recumbent and aligned with the direction of flow. It is a common type and is often found superimposed on other forms. Cf: *corded pahoehoe; elephant-hide pahoehoe; entrail pahoehoe; festooned pahoehoe; sharkskin pahoehoe; shelly pahoehoe; slab pahoehoe* (Gary *et al.*, 1972).

slump scarp. A low cliff or rim of thin solidified lava occurring along the margins of a lava flow and against the valley walls or around steptoes after the central part of the lava crust collapsed due to outflow of still molten underlying layers; the inward-facing cliff may be several meters high (Gary *et al.*, 1972).

spatter [pyroclast] n. An accumulation of small pyroclastic fragments. ----adj. Pertaining to the forms of such accumulations, e.g., *spatter cone*, spatter rampart. Syn: *driblet* (Gary *et al.*, 1972).

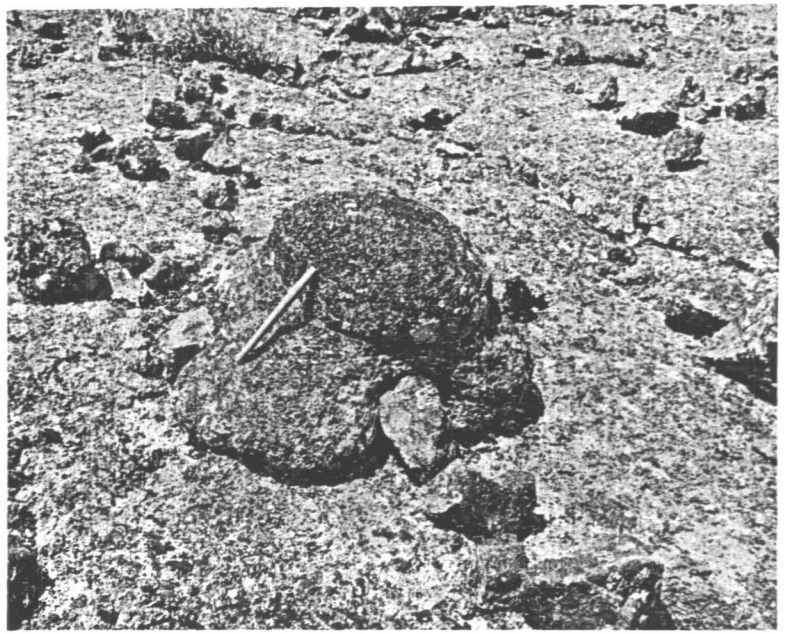
spatter cone. A low, steep-sided cone of *spatter* built up on a fissure or vent; it is usually of basaltic material. Syn: *volcanello; agglutinate cone* (Gary *et al.*, 1972).



Spatter cones on a Mauna Loa rift zone. Photograph by Ronald Greeley, University of Santa Clara, June, 1974.

spatter rampart. Low wall of coagulated spatter produced by fountains of very fluid lava erupted from fissures (Wentworth and Macdonald, 1953).

squeeze-up. A small extrusion of lava from a fracture or opening on the solidified surface of a flow, caused by pressure. It may take various forms, generally bulbous or linear, and may be from a few centimeters to almost a meter in height. It may be marked by vertical grooves. Syn: *push* [volc] (Gary *et al.*, 1972).



Bulbous squeeze-up in the Great Rift lava flow, Snake River Plain, Idaho. Pen indicates scale. NASA-Ames photograph by Mike Lovas, 1969.

tephra. A general term for all *pyroclastics* of a volcano (Gary *et al.*, 1972).

toe [volc]. *lava toe* (Gary *et al.*, 1972).

tuff. A compacted pyroclastic deposit of volcanic *ash* and dust that may or may not contain up to 50% sediments such as sand or clay. The term is not to be confused with *tufa.* Adj: *tuffaceous* (Gary *et al.*, 1972).

tuffite. A term used in Germany for a tuff containing both pyroclastic and detrital material, but predominantly pyroclastics (Gary *et al.*, 1972).

tufflava. An extrusive rock containing both pyroclastic and lava-flow characteristics, so that it is considered to be an intermediate form between a lava flow and a *welded-tuff* type of *ignimbrite.* Whether or not it is actually a genetically distinct type of rock is a matter of debate. Also spelled: *tuffolava; tuff lava; tuflava.* Cf: *ignispumite* (Gary *et al.*, 1972).

tumescence. The swelling of a volcanic edifice due to accumulation of magma in the reservoir. It may or may not be followed by eruption. Syn: *bulge; inflation* (Gary *et al.*, 1972).

tumulus [volc]. A doming or small mound on the crust of a lava flow, caused by pressure due to the difference in rate of flow between the cooler crust and the more fluid lava below. Unlike a ***blister***, it is a solid structure. Pl: *tumuli.* Syn: ***pressure dome*** (Gary *et al.*, 1972).

volcanic. (a) Pertaining to the activities, structures, or rock types of a volcano. (b) A syn. of *extrusive* (Gary *et al.*, 1972).

volcanic breccia. (a) A pyroclastic rock that consists of angular volcanic fragments that are larger than 2 mm in diameter and that may or may not have a matrix. Cf: *agglomerate.* (b) A rock that is composed of accidental or nonvolcanic fragments in a volcanic matrix. Syn: *alloclastic breccia; lava breccia* (Gary *et al.*, 1972).

volcanic chain. A linear arrangement of a number of volcanoes, apparently associated with a controlling geologic feature (Gary *et al.*, 1972).

volcanic cluster. A group of volcanic vents in apparent random arrangement, in contrast to an arrangement over a fissure or other structural control (Gary *et al.*, 1972).

volcanic cone. A conical hill of lava and/or pyroclastics that is built up around a volcanic vent. Syn: *cone* [volc] (Gary *et al.*, 1972).

volcanic dome. A steep-sided, rounded extrusion of highly viscous lava squeezed out from a volcano, and forming a dome-shaped or bulbous mass of congealed lava above and around the volcanic vent. Portions of older lavas may be elevated by the pressure of the new lava rising from below. The structure generally develops inside a volcanic crater or on the flank of a large volcano, and is usually much fissured and brecciated. Cf: *lava dome.* Syn: *tholoid; dome volcano; cumulo-dome; cumulo-volcano* (Gary *et al.*, 1972).

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1. A CONCISE HISTORY OF HAWAII

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1. A CONCISE HISTORY OF HAWAII

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The name "Hawaii" is believed to be a form of "Hawaiki," the legendary ancestral homeland of the Polynesians. Modern research seems to confirm the ancient tradition that the original settlers of Hawaii came first from the Marquesas (500 to 700 A.D.), and later from the Society Islands (1200 A.D.). It is thought that the first Hawaiians crossed the 4370 km of open water from the South Seas to Hawaii in double-hulled canoes that were about 23 m long. The motivating forces behind the perilous journey remain uncertain; however, one theory suggests that a group of Polynesians fled their South Seas home when a neighboring chieftain took over their island and attempted to force new gods upon them. Rather than accept the new gods, it was decided to flee their homeland and follow directions given in an ancient chant, which told of a sea route to new lands. The chant, and a few Pacific storms, led the courageous Polynesians to Hawaii.

The first settlers brought with them such dietary staples as taro, coconuts, bananas, breadfruit, sugar cane and sweet potatoes. They also brought pigs, chickens, and dogs. The migration fleet consisted of many canoes, some of which returned for friends and relatives after the original settlement. Crops were planted and the population gradually spread over the main islands in the Hawaiian chain.

Rivalry among chiefs on the various islands developed and the early history of Hawaii saw much warring between neighboring chiefs, resulting in the development of a feudalistic society not unlike that in Europe. The ruling class consisted of the chiefs, called the *alii*, a rank which was inherited. The stronger chiefs became kings. Next came the priests, the *kahunas*, who foretold the future, functioned as the medicine men, and supervised the placement of temples and the building of canoes by studying the omens. Most of the population were fishermen, farmers or laborers who, in return for protection, provided the *alii* with food, implements, feathers, or *tapa* (the inner bark of the mulberry tree, which was beaten thin and used as cloth). The slave class occupied the lowest rung on the social ladder. Since all the land belonged to the chiefs, the power to put a man off the land he farmed lay with the chief.

From the early days of Hawaiian history until 1846, the land was held by the kings; the concept of private ownership of land was unknown. The *kapu* (tabu) system, closely tied to the Hawaiian religion, consisted of rules for regulating society. The penalty for breaking a kapu was often death and ignorance of the kapu was not considered an excuse. Kapus that called for the death penalty included a man's shadow falling on the house of a chief, crossing of a fence or line surrounding the residence of a chief, and, in the case of women, eating such kapu foods as coconuts or bananas. Another kapu prevented men and women eating under the same roof. The people lived in fear and apprehension of the king since life or death was at his whim. The court of the king seemed to be the easiest life, and generally the safest; the courts of the ancient kings, therefore, were quite large.

Life was difficult for the common man. The kapus called for him to build separate thatched houses for sleeping, eating, worshipping his idols, and tapa beating. Additionally, the man prepared the food for himself and his wife (separately). Men generally wore a loincloth and women wore a skirt made of tapa. The early Hawaiians fashioned implements for everyday life, as well as for war, from bone, shell, stone and wood. Their featherwork was unexcelled.

The early Hawaiians followed their old Polynesian religion, which was a form of nature worship. They believed in a supreme being, but also in hundreds of other gods, some of which were in the form of idols. The most important were: Kane, father of all living creatures; Ku, the war god; Kaneloa, ruler of the land of departed spirits; Lono, god of the harvest; and Pele, the goddess of the volcanoes.

Approximately a thousand years after the original settlement, Captain James Cook accidentally came upon the islands on a voyage from the South Pacific to the northwest American coast in 1778. Cook called his discovery the Sandwich Islands, in honor of his patron, the Earl of Sandwich. He returned to the islands early the following year with his two ships, HMS *Discovery* and HMS *Resolution*. When Cook put into Kealakekua Bay on the island of Hawaii, a religious festival to the god Lono was in progress. Cook was hailed as the reincarnation of Lono and was welcomed by the natives in the true *aloha* spirit. Cook left after two weeks, but was forced to return when a mast on one of his ships was damaged in a storm. Trouble developed, however, when natives stole some iron tools from the ship and Cook went ashore to demand hostages against the return of the stolen items. A fight ensued and Cook was killed, but the news of his discovery spread and ever-increasing numbers of foreigners began to arrive in Hawaii.

After Captain Cook opened the way, other ships came to obtain supplies on their way to China. Their demand for supplies upset the Hawaiian economy, and the conduct of the sailors weakened the old kapus and the ancient culture. At this same time, there emerged a young warrior named Kamehameha (1758-1819), who launched a campaign of conquest that eventually led to his control of all of the inhabited Hawaiian islands.

By 1790, Kamehameha I had conquered the islands of Hawaii (his home island), Maui, and Molokai. In 1795, he set sail for the heavily populated Oahu with a fleet of a thousand double-hulled canoes. In addition to the ordinary native weapons, Kamehameha's warriors carried firearms acquired from foreign ships. Kamehameha completed his takeover of Oahu by driving the opposing forces over the Nuuanu Pali (cliff) near Honolulu. Afterward, Kauai was persuaded to join voluntarily, and by 1810, the first unification of the Hawaiian Islands was complete.

Kamehameha the Great proved to be a wise ruler who enriched the lives of his people. He understood how to deal with foreigners and used them to promote the welfare of his kingdom. He engaged in foreign trade and his rule was a peaceful era of growth. Kamehameha issued laws and encouraged agriculture. A flourishing trade in sandalwood was begun during his reign. Sandalwood was in great demand in the Orient to be used for temple incense and woodcraft. Unfortunately, the trade flourished at such a rate that within two decades the islands were stripped of the fragrant wood.

Kamehameha I lived and held court at Kailua-Kona on the Big Island of Hawaii until his death in 1819. He was loved by the people and his death was grievously mourned. The bones of Kamehameha the Great were placed in a secret cave somewhere in the cliffs along the Kona coast. The exact location of the burial cave remains unknown today, and Hawaiians rejoice that "only the stars know the resting place of Kamehameha."

Upon Kamehameha's death, his son, Liholiho (1797-1824), was proclaimed ruler under the title of Kamehameha II. Under the influence of his mother, one of his first acts was to abolish the kapu system and idol worship. The religious void was soon filled, however, with the arrival of the first American Protestant missionaries from New England in 1820. They were made welcome, and the first Catholic priests arriving in 1827 found that Protestantism was already widespread. Mormon missionaries arrived in 1850 and had some success. While on a visit to England to visit King George in 1824, King Kamehameha II and his wife contracted measles, to which the Hawaiians had no immunity. Within a few days, both died.

At the age of eight, Kauike-aouli (1813-1854) succeeded his older brother, Liholiho, as King Kamehameha III. The court prophet predicted that his name (which meant 'surrounded by black clouds') indicated that trouble would surround him in the form of foreigners. His mother, the wife of Kamehameha the Great, served as Regent during his minority. True to the prophecy, the thirty-one-year reign of Kamehameha III was a period of international troubles for Hawaii.

The missionaries were an important influence on Hawaii. Because education was considered a foundation of religion, the missionaries established schools, transcribed the Hawaiian language and set up the first printing presses in Hawaii. By 1838, the entire Bible had been printed in the Hawaiian language, and by 1840 Hawaii was essentially a Christian nation with a school system supported by the church and state. The missionaries also brought the first ideas of constitutionalism to Hawaii.

Whalers arrived in increasing numbers. The year 1846 was the peak year of whaling with 596 ships entering Hawaiian ports, such as Lahaina on the island of Maui. The Islands offered an important source of food supplies, a haven from Pacific storms, convenient bays for making ship repairs, and hospitable "refreshment" for the crews. They also offered a convenient stopover on the long China trade route, and the United States, France, and Britain vied for increasing control.

Westernization of the Islands grew progressively easier as the Hawaiian people, exploited and diseased by foreign contacts, began dying out with alarming rapidity. The Hawaiian population, estimated at about 300,000 when Captain Cook first visited the islands in 1778, had fallen to about 135,000 by 1819. By 1850, only 85,000 Hawaiians remained. Even before the native population sank to 40,000 in 1890, the sugar plantations had already begun to import Chinese, Japanese, and Portuguese to meet the labor shortage. Hawaii had become a "melting pot."

The foreign influx brought continuing pressures on Kamehameha III to appoint resident aliens as advisers to help him deal with the foreigners. The foreign advisers changed Hawaii's form of government drastically and this spelled disaster for continuation of the old life in Hawaii. The first constitution, which provided for a representative body of legislators elected by the people, was set up in 1840. Another great change under Kamehameha III was the Great *Mahele* of 1848. The Great *Mahele* gave the privilege of land ownership to all

classes – lands that had traditionally been held in trust for the people by their rulers. This one piece of legislation destroyed forever the ancient pattern of Hawaiian life. Under the *Mahele*, the lands were divided among the king, the chiefs, and the commoners. For the first time, land could be bought and sold. Not really understanding the concept of land ownership, many Hawaiians soon found themselves landless. Agricultural expansion, especially in sugar, was made possible by the Great *Mahele.* Too late, King Kamehameha realized the consequences of his act. He died, grief-stricken, at the age of 41.

Alexander Liholiho (1834-1863), twenty-year old grandson of Kamehameha the Great, was proclaimed King Kamehameha IV in 1854. He felt deeply that his troubled nation needed to be freed from foreign manipulating and he set about to accomplish this goal. The young king's rule, however, was tragically shortened. When his four-year old son died, the king lost his will to live and died the following year. His attempts to "free" Hawaii from foreigners were unsuccessful.

The dead king's thirty-three-year-old brother was proclaimed King Kamehameha V (1830-1872) in 1863. He was aloof to both foreigners and his own people, but he did successfully resist the demands of foreigners. He succeeded in drawing up a new constitution to replace the original one, which was principally the work of foreigners, and he promoted an extensive public works program. A major new sugar market developed in recently settled Oregon and California, however, and the king's greatest problem was the demand by the sugar planters for a reciprocity treaty (which would allow exchange of products without paying duty) with the United States. The king's health broke under the strain and his death ended the Kamehameha Dynasty.

The new king, Lunalilo, lived only a short time and David Kalakaua (1836-1891) was voted King of Hawaii by the Legislature in 1874. His queen was Kapiolani and their rule proved to be a popular one. King Kalakaua negotiated a reciprocity treaty with the United States in 1875, and a sugar boom followed. Hawaii was thereafter tied to the United States. The need for more plantation workers brought thousands more to Hawaiian shores. In an effort to offset the increasing alien influence and to preserve the old Hawaiian culture, Kalakaua brought about a renaissance of the ancient dances, music, and chants, which attracted world attention. Writers and musicians from the world over flocked to Kalakaua's "Court of the Bohemians." When Kalakaua attempted to make an alliance with Samoa, however, he ran afoul of the foreign leaders who felt their influence was being undermined. Using the newspapers to spread unconfirmed instances of corruption in Kalakaua's government, the foreigners brought about an armed insurrection in 1887 and forced the King to accept a constitution that would limit his powers. King Kalakaua died in 1891.

The sister of Kalakaua was proclaimed Queen Liliuokalani (1839-1917) in 1891. Her attempts to regain control of the government and replace the constitution that had been forced on Kalakaua led to the overthrow of the Monarchy in 1893. A secret "Annexation Club" had been formed in 1892, and, with the aid of the U.S. Minister to Hawaii and the commander of an American warship stationed in Honolulu, an insurrection occurred in 1893. Liliuokalani was overthrown. When President Cleveland refused to annex Hawaii on the grounds that the U.S. Minister had aided the insurrection, the Republic of Hawaii was established with Sanford B. Dole as president. For plotting a counterrevolution, Liliuokalani was sentenced to twenty-five years at hard labor (the sentence was never carried out). For a time, however, she was held prisoner in the Iolani Palace where she had ruled as queen. It was while she was a prisoner that she composed the beautiful song, *Aloha Oe.*

When the United States became involved in the Spanish-American War, it was decided to annex the strategically located Hawaiian Islands for the protection of the United States. In 1898, the American flag was raised over the Iolani Palace. The United States restored the vote to native Hawaiians and won their affection. World War II paved the way for Hawaiian statehood which was achieved on August 21, 1959.

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2. PHYSIOGRAPHY OF THE HAWAIIAN ISLANDS

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Each of the eight principal Hawaiian Islands extending from Kauai on the northwestern end of the chain to Hawaii at the southeastern extremity represents the top of a great basaltic shield volcano that rises 4575 m above the ocean floor.

The ages of the islands quite consistently decrease toward the southeast. Kauai is judged to be about 5.3 million years old, whereas Hawaii is less than 750,000 years in age. The ravages of time have had serious effects on the once dome-like older volcanoes, so that unless viewed from selected points of observation the traditional shield shape is lost in a fretwork of peaks, ridges, palis, valleys, and plains.

Age is not the only determinant of the degree of dissection by running water, waves, and chemical weathering. Another very important factor is the exposure of the particular side of island to excessive rainfall and mercilous trade-wind wave attack. The windward and high lee slopes receive 60 cm or more of rain annually, whereas the lower leeward slopes and coastal areas may receive 4 cm or less annually.

Brief descriptions of the principal physiographic divisions on each of the major islands follow. These descriptions rely heavily on reference to the Physiographic Divisions as proposed by Abbott (1973).

ISLAND OF HAWAII

The island of Hawaii comprises several major volcanic peaks (Fig. 2–1): Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea.

Kohala Volcano. Kohala provides a splendid example of the difference of erosional dissection dependent on exposure. The northeastern slope displays some of the most magnificent canyons and sea cliffs in the island chain, and yet the southwestern slope is scarcely gullied. The leeward slope slips beneath the water with virtually no cliff at all.

The backbone ridge of Kohala is marked by an alignment of cinder cones formed during the posterosional period of volcanic eruptions.

Mauna Kea Volcano. The highest elevation in the Hawaiian Chain is reached at the summit of Mauna Kea, 4206 m above sea level. The higher portions of the mountain are studded with cinder cones, which indicate a mature or postcaldera stage. Glacial moraines form a prominent shoulder at approximately 3350 m (11,000 ft) elevation. Along the eastern coastline, known as the Hamakua Coast, youthful, amphitheater-headed gullies and valleys incise the lower portions of an otherwise uniform slope. The western and southern slopes are locally deeply gullied, principally by erosive action of glacial meltwaters.

Hualalai Volcano. Hualalai, like Mauna Kea, presents a knobby profile due to cinder and spatter cones that mantle the upper sections. A broad, gently sloping, lava plain borders the foot of Hualalai on the northern and western coasts.

Mauna Loa Volcano. Mauna Loa is the prototype of the shield volcano. Its graceful, majestic lines rise slowly to a summit elevation of 4170 m above sea level. Barren, rough lava flows are typical of the upper slopes. The summit is indented by a large caldera, Mokuaweoweo, and several deep circular pit craters. The northeast and southwest rift zones form prominent ridges descending from the summit.

Kilauea Volcano. The most recently active shield volcano on Hawaii, Kilauea rests on the southeastern side of Mauna Loa. The summit is indented by a large caldera, which in turn contains the crater of Kilauea, known as Halemaumau. On the southern side of the volcano, great terraced fault blocks form a step-like profile. Slopes elsewhere on Kilauea are subdued and gentle. No erosional valleys have yet formed.

MAUI

West Maui is the older, smaller, and more dissected of the two principal shields that join to form the island of Maui. Deeply scoured, Iao Valley replaces the former caldera. Iao Needle, a prominent pinnacle and landmark is a remnant of the ancient caldera fill. Huge radiating amphitheater-headed valleys scallop the outer slopes like spokes on a wheel.

East Maui, or Haleakala Volcano, is joined to West Maui by a low isthmus formed by lavas from Haleakala filling the channel and impinging against the side of the older shield. Layers of sediment sand and soil now mantle the lava rock connection.

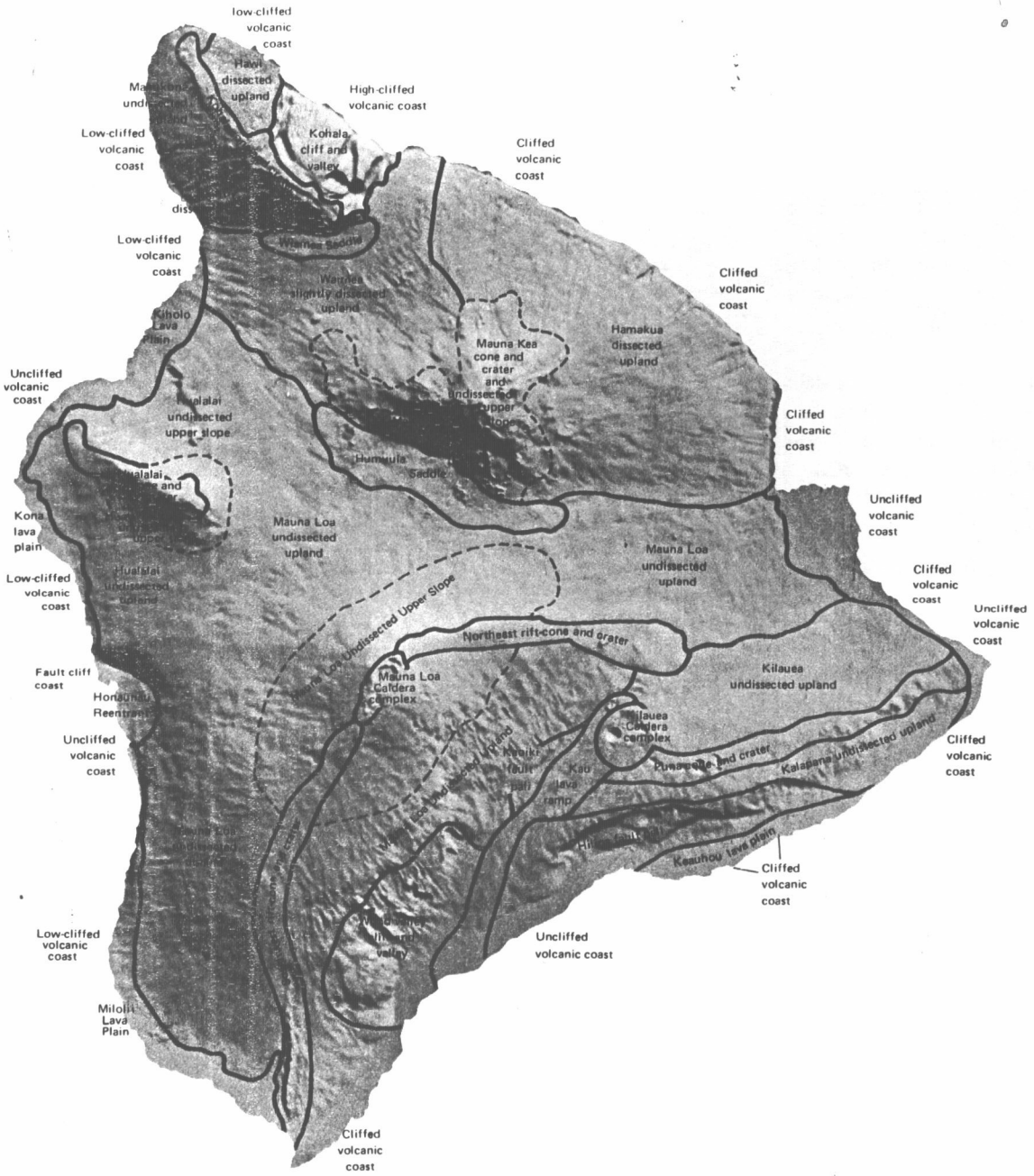

Fig. 2-1. Relief map of the island of Hawaii showing its physiographic regions *(after Abbott, 1973)*.

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The summit of Haleakala culminates in a magnificent crater, partly erosional and partly volcanic. Within the vast crater cinder cones and lava flows form a spectacular highly-colored landscape.

The lower northern and eastern slopes receive 80 cm or more of rainfall annually, resulting in a multitude of youthful gullies and canyons, each containing many waterfalls. The western and southern slopes receive very little rainfall and exhibit features typical of desert areas.

KAHOOLAWE

Kahoolawe is a single low shield. The former caldera is partially scoured out by waves to form steeply cliffed Kanapou Bay. The upland area displays four dissected cinder cones. A thick mantle of reddish lateritic soil deeply scoured by wind and water erosion, and a plateau covered with a blanket of powder-like dust typify the upland section. High, sheer, wavecut cliffs face toward the south.

LANAI

Lanai is also a single volcanic shield. The former caldera is visible in the summit area. It has undergone several stages of collapse.

Huge amphitheater-headed valleys incise the northeastern slope. Most of the rest of the island is cut by gullies of various sizes. On the southwest corner of Lanai Kona, storm waves and a heavy southwest swell have cut a sea cliff 300 m in height.

MOLOKAI

West Molokai, called Mauna Loa, is the older and smaller of two main shields that comprise the island. Gentle arid slopes face west. The eastern side is marked by step-like fault terraces. A strip of wind-blown sand dunes strikes across the northern flats.

The central area of *East Molokai* marks in general the location of the former caldera, which is now carved into a magnificent landscape of great amphitheater-headed valleys, near-vertical cliffs, ridges, peaks, and palis. The north-facing coastline is unique in the world for height and rugged beauty. Vegetation mantled cliffs rise 375 m above the sea.

Kalaupapa is a low late volcanic shield that leans against the steep cliffs on the northern side of Molokai. Principal features are gentle, ungullied slopes, a crater located asymetrically on the shield, and a collapsed lava tube.

OAHU

Waianae Range. The Waianae Range is the older and smaller of two shield volcanoes forming Oahu. Great, broad-floored southwest-facing valleys distinguish the Waianae section. Mt. Kaala is a flat-topped feature on the crest of the range. It is the remnant of nearly horizontal thick lava flows and forms the highest point on the island.

Koolau Range. Lavas from the Koolau eruptions spread westward across the channel to join the Koolau shield with the older Waianae volcano. This saddle now forms the central portion of Oahu. The Koolau range is famous for the 40-km long northeast-facing pali. Great amphitheater-headed valleys cut into the eastern slopes and are well developed on the southern exposures as well. Peninsulas, points, islands, and headlands have been added by late eruptions such as Diamond Head, Ulupau, and the Koko volcanic series.

A broad flat coastal plain clings to the southwest and southern shorelines. Pearl Harbor occupies former dendritic stream valleys that were cut across the coastal plain at the time of a lower stand of the sea.

KAUAI

The central portions of the island of Kauai, which form the high mountainous regions, are controlled by the former presence of a large caldera. Colorful Waimea canyon occupies a structural depression tangential to the caldera boundary. Behind the southerly facing precipitous mountain fronts lies a vast, high-elevation swamp, which is in turn being destroyed by the headward erosion of huge amphitheater-headed valleys slicing deep into the old caldera complex. Alakai swamp and the erosional peak, Mt. Waialeale, which lies on the southern margin of the swamp is in some years the wettest spot on earth, receiving as much as 236 cm of annual rainfall.

The north coast or Napali cliff region displays towering sea cliffs cut by rugged amphitheater-headed valleys that extend deep into the island's interior.

The Lihue and Koloa basins and Kapaa and Princeville uplands are formed on later lavas.

The Mana Plain, which clings to the southwest corner of the island, is a flat, dry sandy coastal plain formed of coral, sediments and alluvium.

NIIHAU

The central upland of Niihau is the erosional remnant of the original shield volcano. Later volcanic flows and pyroclastics form the low platform that extends north and south of dissected upland. Sand dunes and playa lakes cover portions of this arid plain.

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3. ORIGIN OF THE HAWAIIAN ISLANDS

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3. Origin of the Hawaiian Islands

Recent studies indicate that the Hawaiian volcanic chain is a result of relative motion between the Pacific plate and a melting spot in the Earth's mantle

G. Brent Dalrymple Eli A. Silver Everett D. Jackson

The idyllic, palm-fringed outposts in the middle of the Pacific Ocean known as the Hawaiian Islands lie at the southeastern extremity of the Hawaiian Archipelago, a broadly linear chain of more than fifty huge undersea volcanoes that extends 3,500 kilometers across the central Pacific sea floor (Fig. 1). Individual volcanoes rise as much as 9,000 meters above the sea floor and reach a diameter of nearly 120 km at their base. In their prime, the volcanoes stand nearly 5,000 m above the sea. These great volcanic edifices are among Earth's largest mountains, although they are now almost entirely submerged beneath the sea (Fig. 2). All these volcanoes cap the Hawaiian Ridge, a pronounced topographic high on the ocean floor, bordered by a moat as much as 700 m deep on both sides.

The volcanoes of the Hawaiian Islands become progressively younger to the southeast, culminating in the presently active volcanoes of Kilauea and Mauna Loa, two of the five that comprise the island of Hawaii. This age progression was first recognized by J. D. Dana (1849, 1890), who noted that the volcanoes in the northwestern part of the archipelago were progressively more eroded than those in the southeast. Dana's conclusions were confirmed by McDougall (1964), who obtained potassium-argon ages on the major islands of the Hawaiian group and showed that the volcanoes decrease systematically in age from Kauai (5.6 million years) to Hawaii (< 0.7 million years).

Near latitude 32° N, longitude 172° E, in the vicinity of Yuryaku Seamount, the Hawaiian Ridge makes an abrupt bend to become the Emperor Seamounts (Fig. 1), a chain of about thirty additional submerged volcanoes that continues northward another 2,500 km, ending near the juncture of the Kurile and Aleutian trenches. The Emperor Seamounts, like the Hawaiian Ridge, form a linear chain, and the individual shield-shaped volcanoes cap a gentle rise that is bordered by a moat. With few exceptions, the volcanoes of the Emperor chain resemble those of the Hawaiian chain in form and size, and the two great linear features are thought to have a related origin.

This elbow-shaped lineament of more than eighty huge volcanic mountains is one of the most remarkable geologic features on Earth. What processes, operating over what period of time, could account for it? The answers to these questions are incomplete, but it now seems probable that the origin of the Hawaiian-Emperor chain of volcanoes is related to movements of the Pacific plate, the great crustal slab that underlies the Pacific Ocean (see D. P. McKenzie, *American Scientist*, July 1972).

In 1963, J. Tuzo Wilson proposed that the Hawaiian volcanoes were formed as the lithosphere (the term applied to the Earth's crust and the rigid part of the upper mantle) beneath the Pacific Ocean moved slowly northwestward over a fixed "hot spot" in the deeper part of the mantle. This heat source successively supplied magma to form the volcanoes (Wilson 1963). In 1972, W. J. Morgan extended Wilson's idea to include the Emperor Seamounts, which, he argued, were a continuation of the Hawaiian Ridge. He suggested that

Figure 1. Bathymetry of the Hawaiian Ridge and Emperor Seamount chain (after Chase et al. 1970). These two chains are composed of more than 80 huge shield volcanoes, all of which are now thought to have a common origin. The contours indicate the depth, in fathoms, below sea level; the contour interval is 600 fathoms.

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Dr. Silver received his Ph.D. in oceanography from Scripps Institution of Oceanography in 1969 and joined the Geological Survey's marine geology program in 1970. He has concentrated much of his research on the effects that moving lithospheric plates have on the structure and development of continental margins. His major regions of study have been the continental margins off the western United States and northern Venezuela. Dr. Silver's interest in the Hawaiian-Emperor chain has been in helping to develop a useful tool for measuring the history of plate motions and a better understanding of the driving mechanism of plate tectonics.

Dr. Jackson received his A.B. in 1950 and his Ph.D. in 1960 from UCLA. He is a member of Phi Beta Kappa and Sigma Xi and a fellow of The Geological Society of America, The Mineralogical Society of America, and a number of other scientific organizations. Well-known for his work on layered intrusions and their ore deposits and for studies of the nature of the upper mantle of the earth, Dr. Jackson has also been heavily involved in the lunar program, particularly in astronaut training and the petrology of lunar rocks. He is the author of more than 80 publications in these fields. Dr. Jackson joined the Geological Survey in 1951 where he now works in the Branch of Field Geochemistry and Petrology. *The authors wish to thank D. W. Scholl, L. J. P. Muffler, and D. W. Swanson for their helpful reviews of this paper.* *Address: U. S. Department of the Interior, Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025.*

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Figure 1.

the difference in trend of the two chains resulted from a change in the direction of motion of the Pacific plate millions of years ago (Morgan 1972a, 1972b). Variations of these hypotheses have been proposed, but all begin with the idea that the Hawaiian volcanoes form a chain as a result of relative motion between the Pacific plate and some sort of melting spot in the mantle.

These hypotheses, like other broad generalizations about the Earth's behavior and history, evoke a flood of specific questions without simple answers. Are the Emperor Seamounts really a continuation of the Hawaiian Archipelago? What causes the melting spot? Is the spot fixed or in motion? What does the Hawaiian-Emperor chain tell us about the rate and direction of Pacific plate motion? This paper summarizes the available evidence related to these questions, discusses several alternative models for the origin of the Hawaiian-Emperor chain, and points out the directions of current research designed to test these models.

The volcanoes

Hawaiian volcanoes are excellent examples of a type known as shield volcanoes. Above sea level, they are typically broad and smooth with gently sloping flanks that commonly rise less than 50 m per km. Below sea level, the flanks slope more steeply (Moore and Fiske 1969) but are still gentle relative to such classic stratovolcanoes as Mounts Rainier or Fuji. While in their constructional stage, shield volcanoes erupt not only from vents near the summit but also from linear rift zones (Figs. 3 and 4) that pass through the summit and extend out far beneath the sea. The surface expressions of these rift zones are open fractures, collapse pits, lines of spatter and cinder cones, and low lava domes. At depth, the rift zones consist of closely spaced, parallel dikes (Fig. 5).

Fiske and Jackson (1972) have noted that the rift zones of isolated Hawaiian volcanoes, such as Kauai, tend to lie at an angle of about 20° to the trend of the Hawaiian Ridge and may be controlled by fundamental planes of weakness in the lithosphere. Where volcanoes are closely clustered, however, rift zones tend to be oriented parallel to the flanks of neighbor volcanoes.

Hawaiian shield volcanoes erupt lavas of variable chemical composition, usually in a definite sequence. The earliest observed lavas of young, rapidly growing volcanoes and the deepest exposed parts of older ones are invariably composed of a primitive type of basalt called tholeiite; it is therefore generally assumed that the main structure of the volcanoes was formed by copious eruptions of tholeiitic lava. This phase is followed within a few hundred thousand years by a thin capping of alkalic basalt, which is poorer in SiO_2 and richer in K_2O and Na_2O than the tholeiite. During both these volcanic phases, the eruption rate is greater than the erosion rate, and the volcanoes maintain their smooth, shield-shaped forms.

Near the end of the second phase of volcanism, the lavas become more silicic, the eruption rate decreases steadily, and the shields become dissected by deep canyons. Finally, small amounts of nephelinitic basalt, which is even poorer in SiO_2 and richer in alkali metals than the alkalic basalts, may be erupted from scattered vents several million years after formation of the main volcanic edifice. Individual volcanoes may cease activity at any stage before the cycle is complete.

The eruption rates of Hawaiian tholeiitic basalt are the highest known on Earth. Macdonald and Abbott (1970) have estimated that Mauna Loa, which has a volume of about 30,000 cubic km and rises nearly 9,000 m above the sea floor, could have been built in only 1.5 m.y. if it has erupted at its historic rate throughout its lifetime. According to Moore (1970) the combined eruption rate for all volcanoes on the island of Hawaii (derived principally from data at Mauna Loa and Kilauea) averages about 0.05 cubic km per year. Swanson (1972) calculated that the actual magma supply rate to Kilauea has been about 0.1 cubic km per year during the last 20 years, at which rate the volcano would have required less than 0.4 m.y. to reach its present size.

These exceedingly rapid eruption rates have been supported by other data. McDougall (1964) concluded from radioactive age measurements using the potassium-argon technique that most of the subaerial part of each Hawaiian volcano formed in 0.5 m.y. or less. Paleomagnetic data (Doell and Cox 1965) and potassium-argon ages (Dalrymple 1971; McDougall and Swanson 1972) show that the most deeply exposed part of the oldest of the five shields that make up the island of Hawaii formed less than 0.7 m.y. ago, and probably within the last 0.4 m.y. Present-day eruption rates may be reasonable approximations of past eruption rates of all shield volcanoes in the Hawaiian chain. However, some recent observations, to be discussed later, suggest that growth rates may be episodic and that present-day eruption rates may be close to maximum values for the chain as a whole.

Details concerning the exact source of the lava are lacking, but several lines of evidence suggest that it is located deep within the mantle. Earthquakes and seismic tremor have been observed as deep as 50 to 60 km directly beneath Kilauea, and Eaton (1967) has suggested that these phenomena result from the transport of lava from at least these depths to the surface. Seismic refraction studies indicate that the oceanic crust in the vicinity of Hawaii is of normal (5 to 6 km) thickness but that it thickens to 10 to 20 km beneath the Hawaiian Ridge. This crustal thickening is thought to have resulted from the transfer of molten material from the mantle to the crust during growth of the volcanoes. In addition to geophysical evidence, some of the Hawaiian lavas contain angular fragments of exotic, coarsely crystalline rocks (xenoliths), whose mineralogy and texture indicate a depth of origin of more than 60 km (Jackson and Wright 1970).

The volcanoes of the Emperor Seamounts have smooth shield shapes that are very similar to those of the Hawaiian segment, but they are quite distinct from the rougher and steeper topography of other seamounts elsewhere in the Pacific Ocean. The Emperor shields are about the same size as the Hawaiian shields, and in places the bathymetry is detailed

enough to reveal probable rift zones. The main difference between the Hawaiian and Emperor shield volcanoes is their spacing. There are about 18 volcanoes per 1,000 km along the Hawaiian Ridge, whereas for the Emperor Seamounts the spacing is about 13 per 1,000 km. Detailed examination of the bathymetry at the junction of the Hawaiian and Emperor chains shows that neither chain projects beyond the bend (Fig. 1). The available evidence, therefore, supports the idea that the Emperor Seamounts are shield volcanoes that form an older continuation of the Hawaiian chain.

Structure of the chain

Volcanoes of the Hawaiian-Emperor chain appear to have no obvious relation to the age or structure of the sea floor from which they rise. Magnetic data and sediment ages indicate that the sea floor in this area is Cretaceous in age and ranges from about 80 to 120 m.y. old (Heirtzler 1968; Larson and Chase 1972; see Fig. 6). Potassium-argon ages of basalt samples dredged from seamounts near, but not on, the Hawaiian-Emperor chain are also Cretaceous. The oceanic crust in this region of the Pacific appears in no way unusual, and presumably it originated normally at midoceanic spreading ridges during Cretaceous time. Thus the sea floor is definitely older than any of the dated volcanoes in the Hawaiian-Emperor chain.

The position and orientation of both the Hawaiian Ridge and the Emperor Seamounts is oblique to all nearby sea-floor structures. Major fracture zones cross the Hawaiian and Emperor chains at angles of 30° to 40° and 75° to 80°, respectively (Fig. 6). None of these fracture zones detectably disrupts the linearity of the volcanic chain, even though older magnetic anomalies to the east of Hawaii are offset along these fractures by as much as 800 km. Likewise, projected linear magnetic anomalies cross the Hawaiian-Emperor chain at large angles with no obvious change in trend (Fig. 6). Thus it appears that this chain of more than eighty volcanoes was erupted across nearly 6,000 km of older sea floor with little regard for pre-existing sea-floor structures.

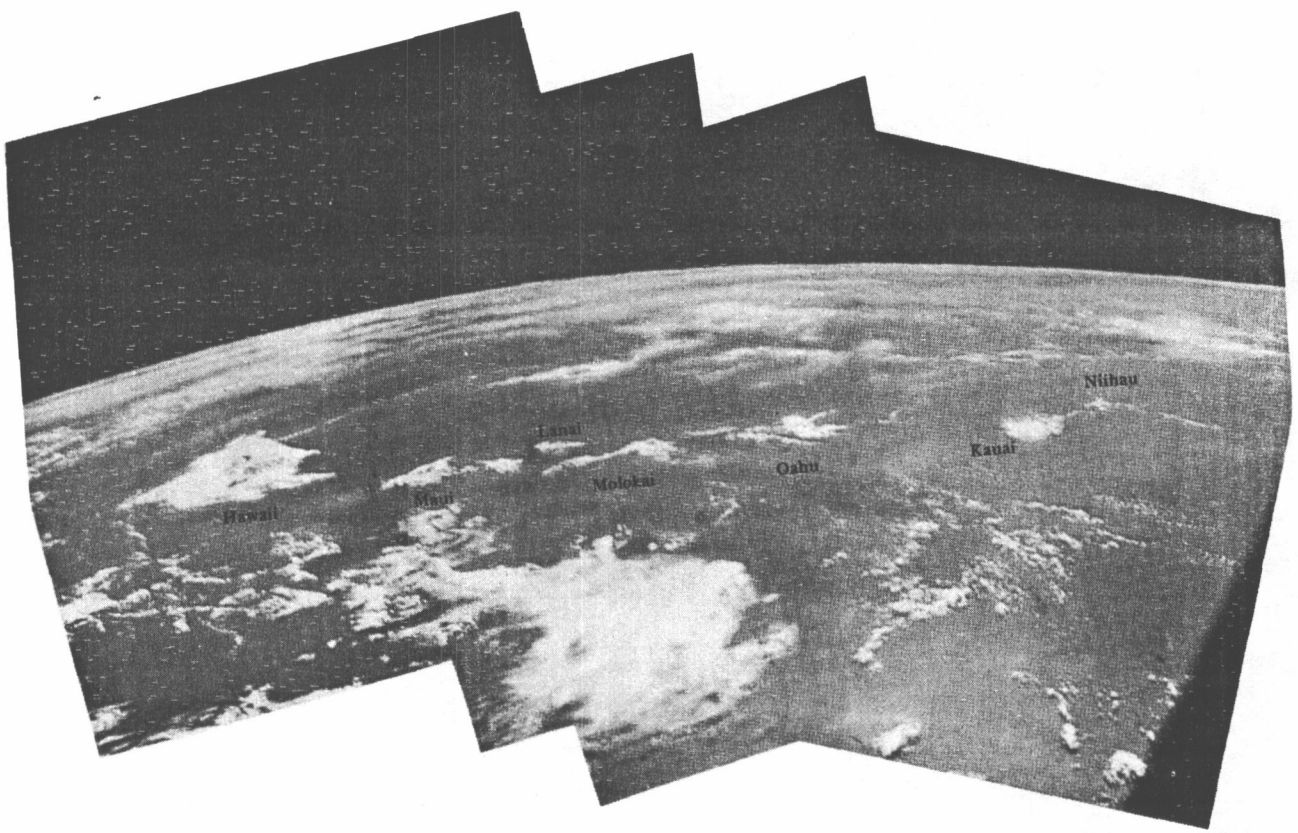

Figure 2. Cloud cover partly obscures the Hawaiian Islands as they were seen by the Apollo 9 astronauts. This view of the island chain is a mosaic of NASA photographs AS-9-3505–3508. (Photos courtesy of the National Aeronautics and Space Administration; mosaic by P. Y. W. Ho and R. L. Tyner.)

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Figure 3 (overleaf). "Curtain of fire" on the southwest rift of Kilauea Volcano, island of Hawaii, during the September 1971 eruption. Note new lava flows in foreground. Shield volcanoes grow by frequent eruptions along such rift zones as well as by summit eruptions. (Photo courtesy of D. W. Peterson, Hawaiian Volcano Observatory, U.S. Geological Survey.)

Thus far, we have described the alignment of shields in the Hawaiian-Emperor chain as linear, but inspection of Figure 7 shows that, in fact, the individual volcanoes appear to lie along a series of short, sigmoidal loci of volcanic centers that are subparallel to each other (Jackson et al. 1972). Looking only at the southeastern Hawaiian Islands, it is apparent that the loci of individual shields, from Molokai south, fall along two curved lines (inset Fig. 7). In addition, available information on the ages of these volcanoes indicates that the order of tholeiitic eruption during the last 1.8 m.y. was West Molokai, East Molokai, Lanai, West Maui, Kahoolawe, Haleakala, Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kilauea. The shields apparently have been advancing simultaneously, but somewhat out of phase, along both the north and south loci. The southern locus can be reasonably extended northwestward through the Koolau, Waianae, and Kauai shields, which are progressively older. Beyond Kauai, however, no simple extension is possible, and the locus appears to end.

Northwest of Kauai, the volcanoes are either submerged or deeply eroded, and their central vent areas cannot be directly located. In the well-exposed southeastern shields, however, the central vent area of each volcano is marked by a topographic high, a positive gravity anomaly, and a pattern of radiating rift zones with unique topographic expression. Using these features as guides, we have located the probable central vent areas of all shields in the Hawaiian-Emperor chain and found that these too lie on smoothly curved loci (Fig. 7).

Although the cause of these loci is uncertain, their general *en echelon* arrangement suggests that they may be related to regional extensional strain. The idea is supported by the fact that the rift zone orientations of isolated volcanoes are parallel to the loci. Presumably, both kinds of structures reflect the direction of maximum principal stress in the Pacific plate in this area.

Geochronology of the chain

The Wilson hypothesis and its subsequent variants predict that the shield volcanoes of the Hawaiian-Emperor chain are progressively older toward the northwest. Thus the radiometric ages of individual volcanoes are a most critical test of mechanisms proposed to explain the progression. Ideally, we would like to know the time that each volcano in the Hawaiian-Emperor chain first erupted onto the sea floor, but these inceptive extrusive rocks were quickly buried by succeeding ones, and thus we must be satisfied with a less direct approach. As a practical alternative, we have taken the oldest potassium-argon date for tholeiitic volcanism on individual shields as the best available approximation of the age of each volcano. This approach is probably reasonable because we know that Hawaiian shields grow rapidly, particularly when erupting tholeiitic lava. In fact, for volcanoes older than about 30 m.y., the growth time is probably smaller than the error in the available dating techniques, which typically is 3 to 5 percent.

Only fifteen volcanoes in the Hawaiian-Emperor chain have been radiometrically dated; their ages are plotted as a function of distance from Kilauea in Figure 8. Ages of the volcanoes from Kauai to Kilauea fall along a remarkably smooth curve, which indicates that the progression of volcanism on the two most recent loci has been systematically accelerating. Shaw (in press) has noted that an increase in lava volume accompanied this acceleration (Fig. 9); it is apparent that eruption rates increased as volcanism progressed southeastward.

Unfortunately, the age data are insufficient to determine the rate of progression of volcanism along other loci, but the general relation between distance and lava volume does occur elsewhere in the Hawaiian chain. The limited data suggest that volcanism along the chain occurs in discrete pulses, each pulse forming volcanoes along either a single locus or a set of adjacent loci. During each pulse, volcanism progresses at an accelerating rate along the chain, accompanied by an increase in eruption rates, until the pulse ends and a new one begins. Moreover, the age-distance relations we now have indicate that one pulse may begin before the previous one has ended.

Although several workers, including ourselves, have used linear extrapolations to predict the age of the Hawaiian-Emperor bend, this approach must be used with caution for the reasons given above. As we shall see later, the relation between the volcanic loci and the ages of individual volcanoes is an important factor in deciding between alternative hypotheses concerning the origin of the chain.

Few radiometric ages of Emperor seamounts have been determined, and we can say little about the progression of volcanism along the Emperor segment. We are not entirely sure, for example, that the direction of progression actually occurred as hypothesized, i.e. from north to south. A minimum age of 70 m.y. was obtained from fossils in sediments on Meiji Seamount in the northernmost part of the Emperor chain (Scholl et al. 1971). An apparent age of 41 m.y. for Suiko Seamount was measured on highly altered rocks (Ozima et al. 1970) and is almost certainly a minimum value. The only reliable rock age is 46 m.y. for Koko Seamount, which lies about 300 km north of the bend (Clague and Dalrymple 1973). Considerable effort is now being directed toward obtaining datable samples from the Emperor shields, but it will probably be several years before our knowledge of the Emperor volcanoes is sufficient to allow more than speculation about their exact nature, rate and direction of progression, and origin.

The melting spot

Most recent investigators agree that the Hawaiian chain probably owes its origin to relative motion between the Pacific plate and a zone of melting in the Earth's mantle (Wilson 1963; Jackson and Wright 1970; McDougall 1971; Morgan 1972a, 1972b; Jackson et al. 1972; Shaw, in press). Although data from the Emperor chain are scanty, it seems reasonable to include them in general hypotheses. Before we can explore the relation of melting to plate motion, we must introduce three terms that will be useful in discussing melting processes in the mantle and transfer of magmatic liquids to the surface: *volcanic conduit*, *mantle source volume*, and *melting spot*.

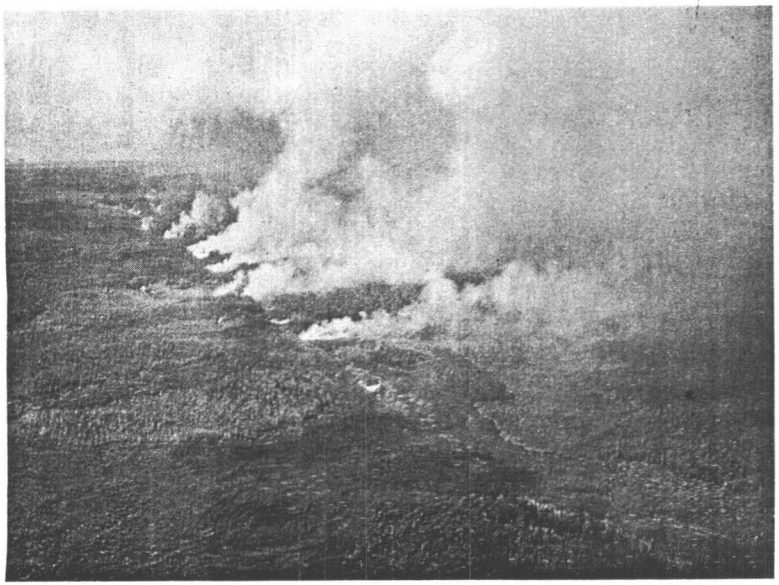


Figure 4. The east rift zone of Kilauea Volcano, island of Hawaii, in eruption March 1965. Approximately 10 km of the rift zone is active in the photograph; the entire east rift system is more than 100 km long. (Photo courtesy of J. G. Moore, U.S. Geological Survey.)

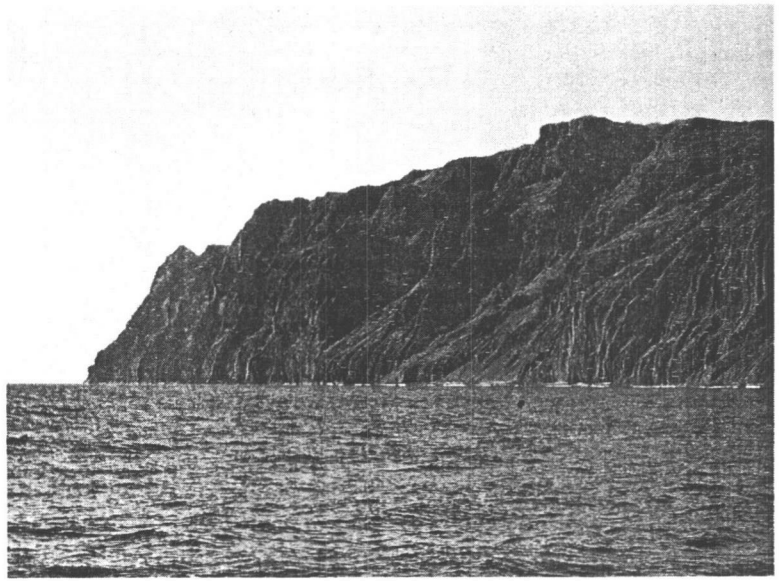


Figure 5. Interior of a typical Hawaiian rift zone exposed by erosion after the volcano ceased to erupt. The rift zone consists of dense vertical dikes that once acted as pathways for lava moving toward the surface. Note that the spacing between the vertical dikes decreases away from the center of the rift zone, which is located near the right edge of the photograph. The horizontal bands between the dikes are lava flows. (Photo by E. D. Jackson.)

We use the term volcanic conduit to describe a system of feeders in the lithosphere through which magmatic liquids rise to feed an individual shield volcano. An individual conduit is not, therefore, a single tube but a complex system of pockets, tubes, and fissures leading upward to a near-surface rift system.

Jackson and Wright (1970) used the distribution of xenoliths on Koolau volcano to suggest that lava rose through a cylindrically shaped conduit with a diameter of about 20 km. Koyanagi and Endo (1971) have shown that present-day swarms of tremor and earthquakes are confined to a conduit about 25 km in diameter at depths of 20 to 40 km beneath Kilauea. The axis of the conduit extends almost vertically downward beneath the summit of the volcano. A 20- to 25-km diameter is consistent with the fact that individual shields maintain their physiographic and compositional identity in time, although they are spaced as close as 40 to 50 km apart (Dana 1890; Powers 1917; Macdonald 1949; Wright 1971).

The mantle source volume, by our definition, is the region in the asthenosphere from which basalt is melted from its parent rock. The source volume can be no smaller than the diameters of the conduits through which lava rises to feed individual shields. Shaw (in press) calculates the cross-chain width of the source volume to be about 75 km, considering that four loci are accommodated across the 300 km width of the chain at Midway. From considerations involving the rate of volcanism, he estimates that the source volume is about 140 km long parallel to the chain, and that it is about 50 km thick. From these data, he calculates a source volume for each shield of

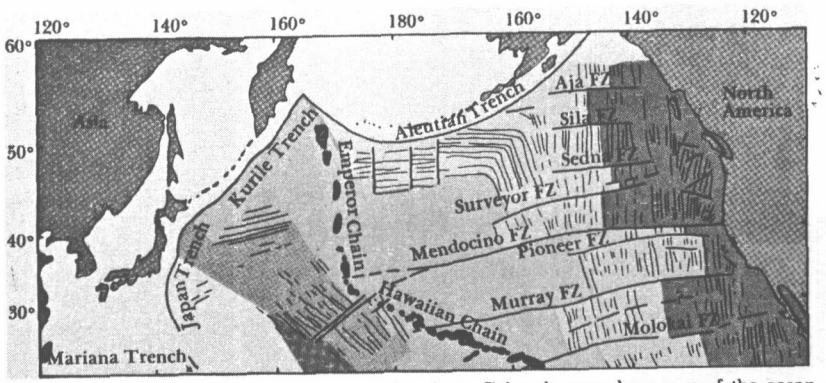


Figure 6. Magnetic lineation and structural features of the North Pacific (after Hayes and Pitman, 1970, by permission of the Geological Society of America). FZ = fracture zone; lines perpendicular to fracture zones represent magnetic anomalies on the ocean floor. Colored areas show ages of the ocean floor (after Larson and Chase 1972). Red areas are <40 m.y. old; blue 40–80 m.y.; yellow 80–120 m.y.; green 120–150 m.y.; and orange >150 m.y.

about 500,000 cubic km. If the average volume of a shield is taken as about 20,000 cubic km, then the percentage of mantle melted to obtain the basalt is approximately 4 percent.

We use the term melting spot to describe a region of finite size in the mantle within which tholeiitic magma is generated and whose vertical projection on the Earth's surface is an area within which genetically related tholeiitic eruptions have occurred or may occur simultaneously (Jackson et al. 1972). So defined, the melting spot contains more than one volcanic conduit and may contain more than one mantle source volume.

What can we say about the size of the Hawaiian-Emperor melting spot? From the data in Figures 7 and 8 it appears that volcanoes that occur along different loci in a given region may erupt simultaneously. For example, Waianae and Niihau were in their tholeiitic eruptive phases at roughly the same time, and Nihoa is not much older than Kauai. The length of the melting spot along the chain, therefore, is on the order of 200 to 400 km. The width between adjacent multiple loci in the southeastern part of the chain is presently only about 50 km. The multiple loci at Midway, however, give cross-chain distances of about 300 km.

On the basis of present information, the projection of the melting spot on the Earth's surface is, to a first approximation, a circle about 300 km in diameter, whose previous path across the Pacific has been wide enough to include all the volcanoes of the chain (Fig. 7). We do not think the spot is currently centered on Kilauea, but rather northeast of there, because the curvature of the two loci that contain Kilauea and Mauna Loa has carried the volcanic centers far south of the median line of the chain. We predict that a new locus of centers will begin, in the very near geologic future, about 40 to 50 km north or east of Kilauea, perhaps coincidentally on its currently active east rift zone.

In summary, the melting spot within which simultaneous volcanism may occur appears to be roughly circular in plan and to have a diameter of about 300 km. The source volumes for individual shields within the melting spot may be regions about 75 km by 140 km, which lie at depths between 50 and 100 km. The conduits between the source areas and the surface at depths of less than 50 km appear to be roughly cylindrical and about 20 to 25 km in diameter.

Movement of the melting spot

The question of whether the melting spot has remained fixed geographically throughout its history or whether it is in motion relative to the lower mantle is fundamental and extremely important. Using the geometry of linear magnetic anomalies, transform faults, spreading ridges, and ocean trenches, and current knowledge about the way these features form (see D. P. McKenzie, *American Scientist*, July 1972), it is possible to deduce the relative motion, past and present, between adjacent crustal plates.

Morgan (1972a, 1972b) suggested that melting spots in the mantle may provide a fixed reference system for the analysis of plate motions. He proposed that volcanic island chains and aseismic ridges are formed as crustal plates move over these melting spots, that the spots are stationary relative to each other and to the Earth's geographic poles, and that approximately twenty such spots can be identified. In contrast, McDougall (1971) preferred a counterflow system in which the melting spot in the mantle moves at about the same speed but in a direction opposite to that of the crust. Shaw (in press) believes that rates of progression of volcanism along the Hawaiian chain are determined by the physicochemical processes involved in shear melting (described below) and may have a more complex relation to the rate of plate motion.

Morgan concluded that the Hawaiian-Emperor chain is not unique in the Pacific. There are two, and perhaps three, others with similar orientation, length, and geometry (see Fig. 10). Two of these are the Tuamoto-Line Islands and the Austral-Marshall Islands, each with recent volcanic activity at their southeast ends—Easter Island and Macdonald Seamount, respectively. A third possible chain runs northwest from Cobb Seamount, located near the northwest coast of North America, through the Gulf of Alaska to the Aleutian Trench near Kodiak Island.

Morgan has shown that all four volcanic chains could have been formed by movement of the Pacific plate over four fixed melting spots. The Hawaiian, Tuamoto, Austral, and Gulf of Alaska chains all lie on small circles with a common pole at latitude 76° N, longitude 73° W. The Emperor, Line, and Marshall chains lie on small circles with a pole at latitude 23° N, longitude 110° W. The northern end of the chain in the Gulf of Alaska is missing, possibly because it has been consumed in the Aleutian Trench. The peculiar geometry of these island chains does not favor completely independent moving spots; the melting spots must be more or less fixed relative to one another, although they could be moving with respect to some other reference frame. Data on the ages of volcanoes in these other island chains are practically nonexistent, and only the Hawaiian chain is sufficiently well studied to verify, at least partly, the predicted age progression.

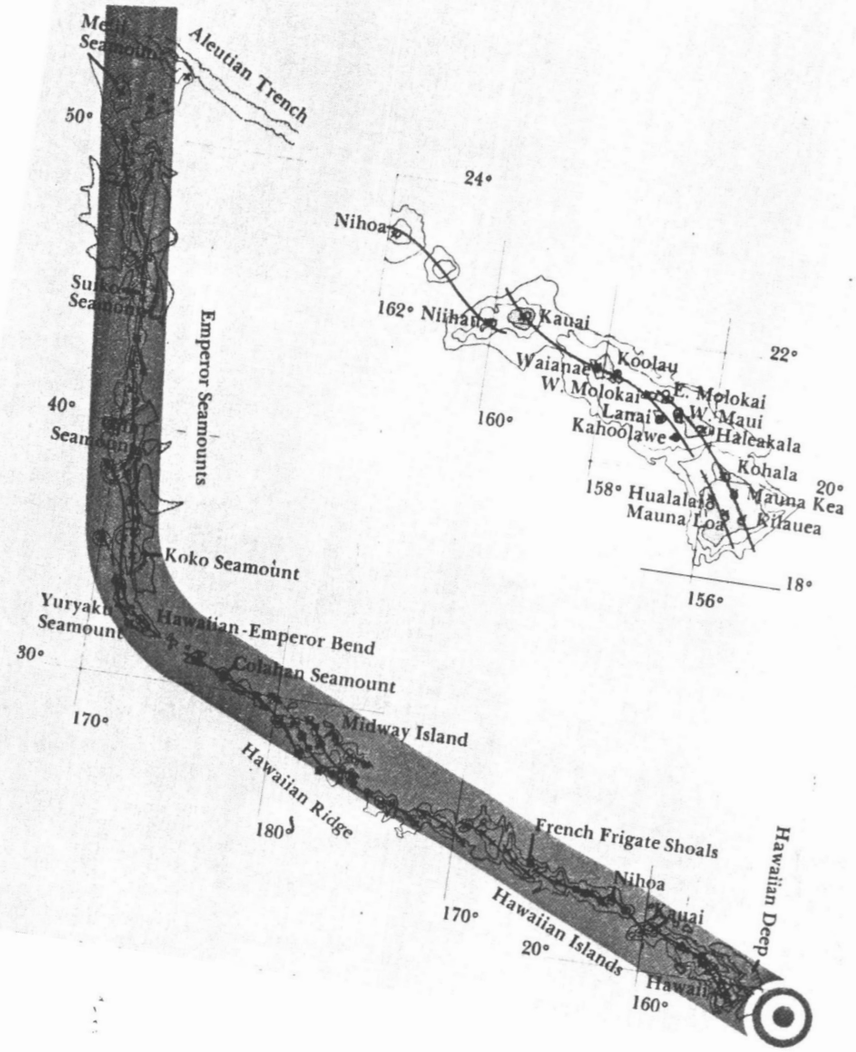


Figure 7. The colored bull's-eye marks the present location of the melting spot in the Hawaiian-Emperor chain, and the colored band the presumed path of the spot across the Pacific during the last 70 m.y. or so. The heavy black lines indicate loci of shield volcanoes. Inset shows the detailed relation between topographic highs (crosses), Bouguer gravity anomaly highs (circles), and loci for the principal Hawaiian islands. (After Jackson et al., 1972, by permission of the Geological Society of America.)

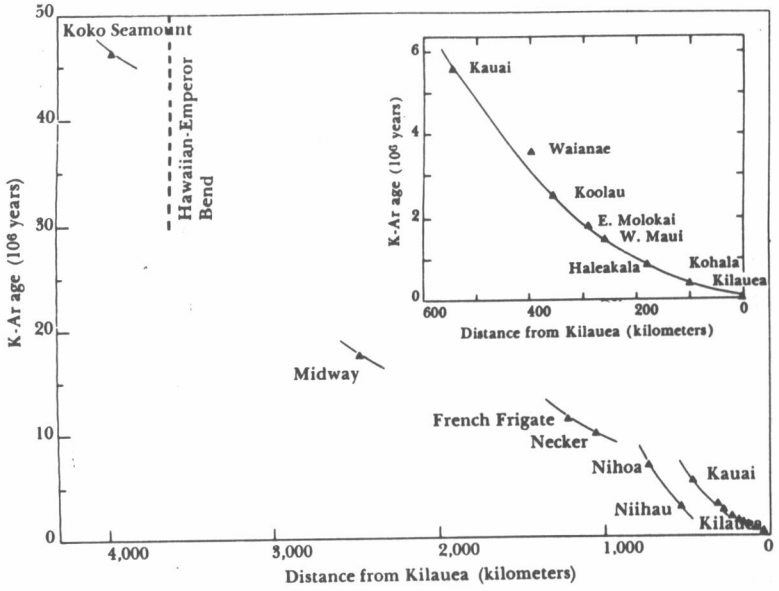


Figure 8. Potassium-argon age of tholeiitic volcanism on the Hawaiian-Emperor chain as a function of distance from Kilauea. Inset shows the detailed relations for the principal Hawaiian islands. Lines connect ages of shield volcanoes that lie on common or adjacent loci (Fig. 7). Although the ages of the volcanoes increase more or less systematically to the northwest along the chain, the age-distance relations are not linear. (Data from McDougall 1964; Dalrymple 1971; Doell and Dalrymple 1973; McDougall and Swanson 1972; Clague and Dalrymple 1973; and unpublished data of the U.S. Geological Survey.)

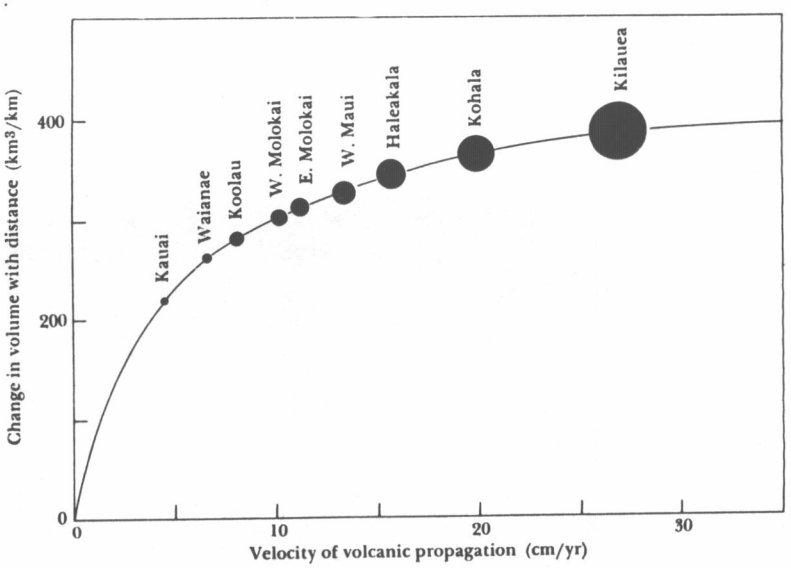


Figure 9. Change in volume of lava with respect to unit distance versus change in distance with respect to time (velocity of volcanic propagation) for the principal Hawaiian islands. The diameter of the circles is proportional to the apparent eruption rates, which have increased during the last 5 to 6 m.y. from about 0.01 cubic km/yr during the formation of Kauai to about 0.1 cubic km/yr for Kilauea Volcano. (Volume estimates from D. A. Swanson; figure after Shaw, in press.)

Grommé and Vine (1972) have made an elegant test of the fixed melting spot hypothesis. They determined the latitude of formation of Midway Island by measurement of the inclination of the remanent magnetism in tholeiitic basalt flows from two holes drilled into the atoll (Ladd et al. 1967). Lava flows, as they cool through the Curie temperatures of their magnetic minerals, record the direction and intensity of the Earth's magnetic field at the time and place of their formation. Because the magnetic and geographic poles are coincident over long periods of time, it is possible to infer ancient latitudes from paleomagnetic data. The results of Grommé and Vine indicate that Midway formed at 15.1 ± 4.1° north latitude. This is not significantly different from the present latitude of Kilauea (19.5° N) but is significantly different from either the present latitude of Midway (28.2° N) or the latitude of about 24° N predicted by McDougall's (1971) moving spot hypothesis.

An indirect test of the fixed melting spot hypothesis has been made by investigations of sediment thickness in the equatorial Pacific Ocean. Present-day sedimentation rates are highest at the equator because of the high productivity of organisms owing to upwelling of nutrient-rich waters. Deep-sea drilling has shown that this equatorial sediment bulge in older sediments is displaced progressively northward from the present equator (Winterer 1973; Clague and Jarrard 1973). If the melting spot is fixed and the Pacific plate has indeed moved northward in time with respect to the Earth's spin axis, one would expect just such a northward shift of the sediment bulge. While these data do not prove that the melting spot is fixed, they are not inconsistent with that idea.

Origin of the melting spot

The hypotheses so far advanced to explain the Hawaiian melting spot have many points in common but generally fall into four categories:

1. The "hot" spot hypothesis
2. The plume hypothesis
3. The propagating fracture hypothesis
4. The shear-melting hypothesis

The "hot" spot hypothesis was originally proposed by Wilson (1963), who envisioned the Pacific oceanic lithosphere as being transported over an area of anomalously hot mantle. The chain of volcanoes that formed by melting from this hot spot drifted northwest like the smoke from a stationary fire (Fig. 11). Jackson and Wright (1970) noted that if this model were correct, the source of materials for melting must be entirely in the lithosphere, which would be heated as it passed above such a thermal anomaly. They calculated that if the lithosphere were 100 km thick, as much as 50 percent melting of the source volume would be necessary to account for the amount of basalt in the shields. This percentage of melting is larger than most recent estimates but is not so high as to be completely unreasonable.

The plume hypothesis, a more advanced version of the hot spot hypothesis, was proposed by Morgan (1971; 1972a; 1972b) to account for the location of certain volcanic centers on the Earth and to provide a mechanism to drive crustal plates. Plumes are supposedly the result of convection and originate deep within the Earth's mantle, possibly near the core (see Fig. 12). They arise because of thermal instabilities (excess heat)

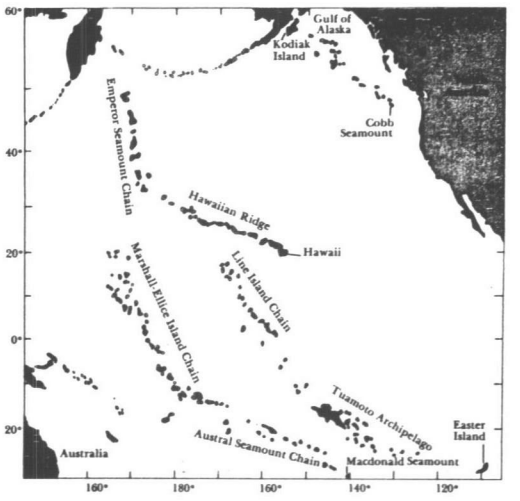


Figure 10. Seamount and island chains in the Pacific Ocean. Morgan (1972a, 1972b) has proposed that the four chains were formed by motion of the Pacific plate over four melting spots, each now located at the southeast extremities of the chains.

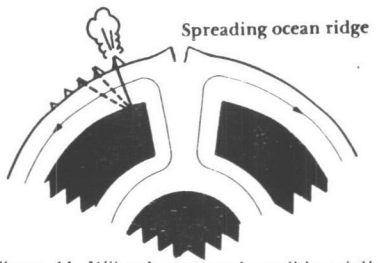


Figure 11. Wilson's proposed possible origin of the Hawaiian Island chain. The diagram shows that if lava is generated in the stable core of a convection cell in the mantle, and the surface is carried along by plate motion, then one source can give rise to a chain of extinct volcanoes. (After Wilson, 1963, by permission of the National Research Council of Canada.)

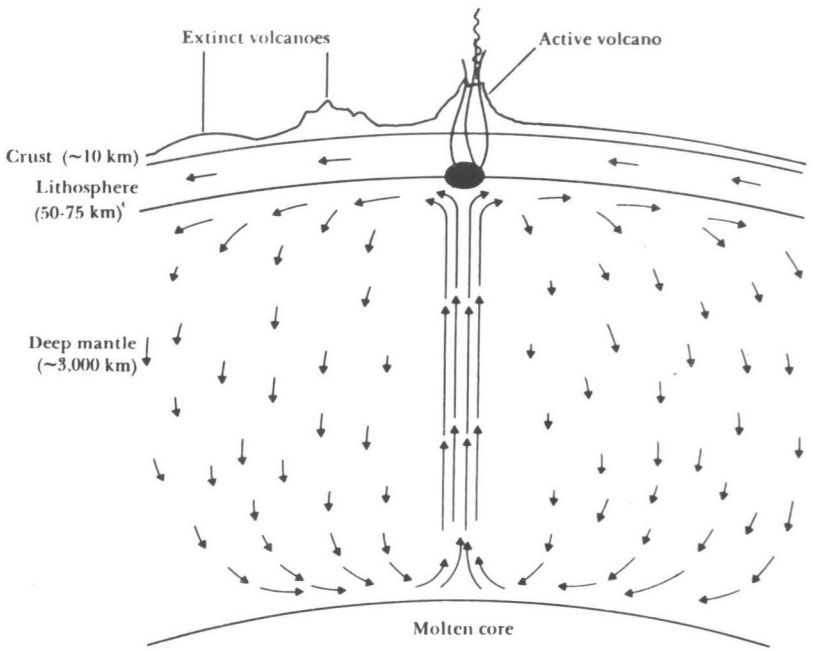


Figure 12. In this schematic diagram of Morgan's proposed plume under Hawaii, hot mantle material streams up in a narrow zone at high velocity (~2 m/yr) from deep in the mantle, causing melting in a region near the lithosphere-asthenosphere boundary. The magma generated pierces the lithosphere, and a volcanic island chain is formed as the Pacific plate moves westward. According to this hypothesis, the plume provides the force for driving the plate. Return flow of mantle material is at low velocity over a large area beneath the Pacific.

which cause upward convection of a hot plume of mantle rock with relatively low viscosity, about 150 km in diameter, in much the same way that thermal instabilities in the atmosphere cause so-called thunderhead clouds, which have a similar plume shape. According to Morgan, these plumes convect upward at a rate of about 2 m per year and not only are responsible for volcanoes but also provide the main driving force for plate motions.

Convection in the mantle is not a new idea, but Morgan was the first to suggest that it was concentrated in such a narrow, high-velocity stream. As the plumes impinge upon the base of the lithospheric plate, the rising material is dispersed and returned to the deep mantle over large areas as a sort of gentle "rain" that migrates slowly downward. Morgan proposes that a low-density fraction (presumably higher in silica and the alkali metals and lower in magnesium and the transition metals like iron) from the Hawaiian plume is "plastered" at the plate-mantle interface, where it accumulates in pockets much like oil trapped in a reservoir. Because the material is gravitationally unstable, it rises through vents to the surface where it forms shield volcanoes. As the plate moves away from the plume head, a new pocket forms, and the existing pocket ceases to be supplied with new material. Material in such an isolated pocket is free to fractionate chemically and provide the late-stage alkalic and nephelinitic lavas common to Hawaiian volcanoes.

The propagating fracture hypothesis has been advanced by several workers (Betz and Hess 1942; Jackson and Wright 1970; Green 1971) but probably is best developed by McDougall (1971). He proposed that the Hawaiian chain is formed by propagation of a tensional fracture caused by a thermal high or incipient upwelling that reflects a concentration of heat-producing radioactive elements in the mantle. This fracture invites further diapiric upwelling of mantle material from the asthenosphere into the lithosphere, and the accompanying pressure release causes partial melting and the formation of tholeiitic lava (Fig. 13).

As the plate and the heat source move away from each other, the pocket of mantle material is isolated in the lithospheric plate, and the cycle of volcanism for that particular volcano is completed in a manner similar to the plume hypothesis. In contrast to the fixed plume model, and in contrast to the propagating fracture models of Betz and Hess and Jackson and Wright, McDougall postulates that the heat source moves with equal velocity as the Pacific plate but in the opposite direction.

The shear-melting hypothesis was recently advanced by Shaw (in press) as an alternative to the plume and propagating fracture models. This hypothesis is based on the observation that a viscous medium will heat up when sheared. As temperature rises, viscosity decreases, allowing an increase in rate of shearing which, in turn, allows a further increase in temperature. Shaw proposed that shearing of the lithosphere over the asthenosphere results in increased temperature and potential melting. When melting begins, magma rises to the surface to form volcanoes. This carries off excess heat, temperature drops rapidly, viscosity increases, and the system begins a new cycle. The process proposed by Shaw thus contains a thermal feedback mechanism that is capable of initiating cycles of rapid melting and accelerated volcanism which terminate abruptly.

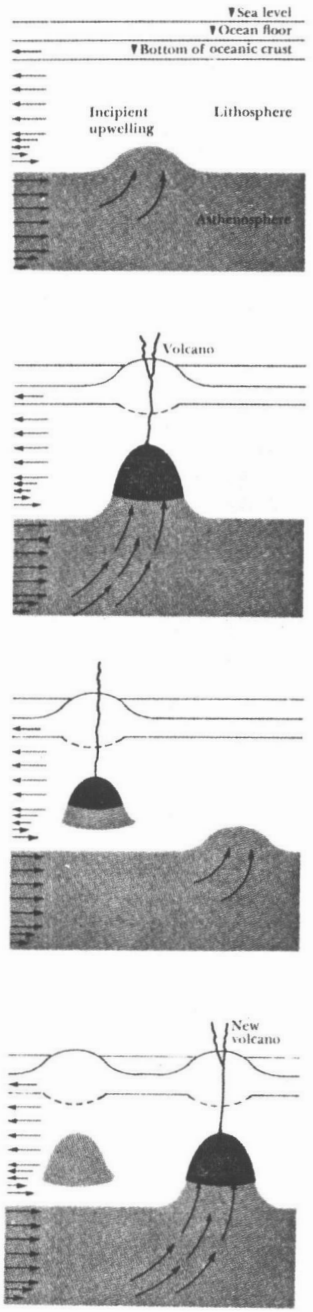
At present there are insufficient data to decide among these various hypotheses, and it is probably premature to accept a single process as the final explanation for large-scale volcanic features of the Hawaiian type. The plume and propagating fracture hypotheses have some attractive features, but neither, as presently developed, accounts for the sigmoidal loci of volcanic centers, the close relation observed between the loci and the ages of the volcanoes, or the remarkably consistent chemical cycle followed by all of the accessible volcanoes. Although both hypotheses call for the generation of magma within or at the base of the lithosphere, geochemical and geophysical evidence indicates that nephelinitic lava is generated at greater depths than tholeiitic lava and that both come from the mantle.

Both hypotheses fulfill the requirement that the melting spot continually either tap fresh mantle material or be resupplied. However, McDougall's hypothesis presently is not consistent with the paleomagnetic evidence discussed above that Midway formed far south of its present latitude. Although Shaw's shear-melting model has many attractive features and seems potentially capable of explaining some of the distance–age–volume relations observed on the Hawaiian chain, it is not entirely clear why the melting should be confined to a single spot.

Finally, both Morgan's plume and Shaw's shear-melting models are in conflict with present knowledge about the rate of migration of volcanism. Morgan (1972a, 1972b) compared the motion vectors between the various plates and the melting spots (as predicted from the known relative motions of the plates) with the observed orientations and rates of formation of the volcanic chains. He found that the melting spots were satisfactory as a fixed reference frame for plate motions only if the average rate of volcanic progression on the Hawaiian chain was 9 cm/yr. Our best estimate, based on recent radiometric ages, yields an average rate of 12.5 cm/yr, in conflict with his prediction. Shaw (in press) predicted an age of about 50 m.y. for the formation of the southernmost part of the Emperor chain, on the basis of his shear-melting model and lava volume estimates, in good agreement with the measured age of about 46 m.y. for Koko Seamount. However, he also predicted an age of about 30 m.y. for Midway Island, which seems well dated now at 18 m.y.

Thus, all models have their strengths and their weaknesses. More detailed geochronological study of the Hawaiian chain and Emperor Seamounts should test whether (1) volcanism progresses linearly with random scatter at about an average rate of 9 cm/yr, as predicted by the plume–fixed spot models, or (2) volcanism is grossly episodic with accelerating rates along individual loci, as predicted from the shear-melting model. Many more paleolatitude determinations, especially on the Emperor chain, are needed before moving spot models can be completely precluded.

In attempting to define the cause of the volcanic activity and of plate motions, we should consider that causes and consequences are not necessarily separate entities. For ex-



ample, convective motions in the mantle may just as well result from plate motions as cause them (McKenzie 1969). In the case of the Hawaiian volcanoes, we face the dilemma of determining whether plate motions cause or are caused by the processes inherent in the origin of volcanic chains, and we may have to conclude that the processes are interdependent. The prospect of discovering the real nature of this interdependence provides the impetus for continuing this exciting research.

Figure 13. Schematic diagram of McDougall's model for the origin of the Hawaiian chain. Relative velocities of the lithosphere and asthenosphere are indicated by arrows to the left of the diagrams. According to McDougall, a propagating tensional fracture initiates diapiric upwelling in the asthenosphere (*top*), resulting in partial melting and tholeiitic volcanism (*second from top*). Relative motion between the lithosphere and the asthenosphere eventually decapitates the diapir (*third from top*), and the cycle begins again in a new location eastward along the chain (*bottom*). (After McDougall, 1971, by permission of Macmillan Journals.)

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4. SYNOPSIS OF VOLCANIC STRATIGRAPHY

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Volcanic stratigraphic units are mappable layered units composed of volcanic rocks that are formed on land (subaerially) or under water (subaqueously) by volcanic processes. At least ten different types of volcanic stratigraphic units are recognized (Table 4-1). The characteristics for each are discussed briefly and some typical examples are illustrated by diagrams to show their salient features.

LAVA FLOWS

Four types of lava flows can be distinguished by their areal characteristics and surface features (Tables 4-1 and 4-2): (1) flood lava flows, (2) pahoehoe lava flows, (3) aa lava flows, and (4) block lava flows.

Flood lava flows issue from fissures (Figs. 4-1 and 4-2) and involve extremely fluid (mafic) pahoehoe lavas. They have uniformly smooth to hummocky or pitted surfaces. Flow margins range from smooth to crenulated. Benches, fractures, and/or pressure ridges may parallel the flow margin, representing former levels of lava ponds. Circular sag structures 80 m or more in diameter may also be present. The sag structures result from withdrawal of lava from beneath a crust during an intermediate stage of cooling of the flow. Molten lava often wells up within the sag structure and fills, or partly fills it.

Pahoehoe lava flows, as distinguished here, are erupted from point-source vents or fissures and are smaller in area than flood flows. They have smooth to irregular surfaces that commonly have anastomosing tongues of individual flows and flow units (Fig. 4-3(a)). The general lava flow direction is often indicated by oriented lava channels and collapsed lava tubes (Fig. 4-3(b)).

Aa lava flows have irregular surfaces composed of clinkers and rubble (Fig. 4-3(c)). Lava channels, leveed channels (many with steep levees), and flow lines often extend parallel to the flow direction.

TABLE 4-1.– SUMMARY OF VOLCANIC STRATIGRAPHIC UNITS

Stratigraphic Unit	Definition	Areal Extent*	Thickness
LAVA FLOWS			
Flood lava (pahoehoe basalt) Composed of compact lava and scoriaceous breccia.	Most fluid lava of great volume. Pours out from fissure 1/2–10 km long at high rate. Inundates low-lying topography. Cools after ponding. Top surface is hydrostatic level. Surface is smooth or pitted by collapse. Rare fluidal layering.	Distal; 100 to >100,000 km^2	<10 to 100 m
Pahoehoe lava (basalt-andesite) Composed of compact lava and scoria	Fluid lava of considerably lesser volume than flood lava. Derived from fissure or central vent. Confined to topographic lows. Often feed through central tube, branching at front. Advances as digital lobes. Surface is smooth to irregularly pitted. Tube roofs collapse to form discontinuous channels. Rare fluidal layering.	Distal, proximal; one to 1000 km^2	<10 m
Aa lava (basalt-andesite) Composed of compact lava, flow-breccia, and scoria.	Sluggish to moderately fluid lava of low volume. Derived from fissure or more commonly a central vent. Confined to topographic lows. Often feed through central channel. Advances as a massive rubble front. Surface is irregular with longitudinal furrows and pressure ridges, levees, and gutters; covered with rubble of angular spinose blocks, commonly large masses of rafted cooled crust. Fluidal layering is common.	Proximal; one to 100 km^2	<10 m
Blocky lava (basalt to rhyolite and trachyte) Composed of compact lava, flow-breccia, and monolithic to pumiceous breccia.	Most sluggish lava, of small volume. Derived from central vent or tholoid. May not be confined to topographic low but occur as lobate mass on sloping terrain. Feed in mass, pushes forward; advances as a massive rubble front, shoves levees aside as front widens. Surface is irregular, furrowed by longitudinal fractures and levees, concentric pressure ridges. Fluidal layering is characteristic.	Central 1 to 10 km^2	10 to 100 m
SUBAQUEOUS and INTRAGLACIAL DEPOSITS (basalt) Form complexes of dense lava, pillow-palagonite breccia and hydroclastic tuff.	Subaqueous deposit forms a pod-shaped complex peripheral to source. Grades laterally or abruptly into tuffaceous sedimentary rocks. Consists commonly of central mass of compact dense lava, surrounded by a carapace of pillow-entrail basalt and palagonite tuff. Some pillow basalt and tuff may form core. Intraglacial deposit forms in glacial lake. Similar to subaqueous deposit but tends to have more complex internal structure. May be capped by pillow and/or compact lava to form a crown; deposit then called a tuya.	Central 1 to 100 km^2	10 to 50 m

TABLE 4-1.– SUMMARY OF VOLCANIC STRATIGRAPHIC UNITS – Concluded

Stratigraphic Unit	Definition	Aeral Extent*	Thickness
LAHARS Formed of tuff-breccia, lapilli-breccia, lapillistone, and lapillituff of varying compositions.	Fluvially deposited tuffaceous, pumiceous, and/or lithic-rich breccias and conglomerates. Derived from volcanic center or originate on volcanic flank. Well compacted. Appear massive. Poorly stratified. Have crude clastic-size layering or density stratification. Smooth, boulder strewn surfaces. Confined to topographic lows. Drain away down valley, leaving levees as high marks. Fluvial current structures common along margins and at terminations. Digital fronts.	Distal, proximal; 1 to 1000 km^2	10 to 100 m
DEBRIS AVALANCHE DEPOSITS Block and ash deposits. Composition similar to mudflows.	Hot gas-charged, mixed block, lapilli, pumice, and ash deposits. Derived from volcanic center – crater or adventive cone. Friable, moderately compact. Appear massive. Discontinuously stratified with pumice, lithic, and/or coarse ash lenses. Irregular surface, marked by pressure ridges near foot of deposit and parallel fluted, downslope-trending ridges near upper part of deposit. Confined to volcano slope and base. May grade laterally into pyroclastic flow or mudflow.	Central 1 to 100 km^2	10 to 50 m
PYROCLASTIC FLOWS Similar to mudflows and avalanche deposits, but with lesser percentage of coarser fragments; of silicic composition.	Similar to debris avalanche deposits. Distinguished by smooth, boulder strewn surface, marked by irregular pressure ridges. Confined to volcano slopes and topographic lows. Broadly lobate front.	Distal, proximal; 1 to 1000 km^2	10 to 200 m
IGNIMBRITES, ASH–FLOWS Similar to pyroclastic flows with still lesser percentage of coarser fragments.	Hot gas-charged mixed block, lapilli, pumice, and predominately ash sheet-like deposits. Derived from volcanic center, adventive cone, or fissure. Friable to highly indurated, lithoid, and compact. Massive. Stratification produced by differentially welded and crystalline zones. Smooth surface, mantled by ash and pumice. Confined to topographic lows. Broadly lobate front, thinning to zero thickness.	Distal, proximal; 100 to 100,000 km^2	10 to 100 m
ASH–FALL DEPOSITS Composed of pumice, ash, uncommonly of basaltic cinders. Forms most tephra deposits.	Blanket deposits of predominantly ash. Derived from crater or adventive cone. Friable; compacted and indurated by burial and cementation. Layered, according to fragmental size, composition, color, and volume of ejecta. Smooth surface mantling existing topography.	Distal, proximal, central Basaltic cinders are central. Extends downwind from volcano 1 to 1000 km 1000 to 1,000,000 km^2	0.1 to 10 m

*Terms central, proximal, and distal relate to areal position of deposit with respect to volcano center.

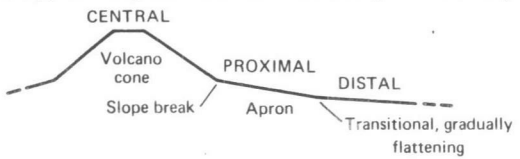


TABLE 4-2.– SUMMARY OF LAVA FLOW DIMENSIONS

Dimension	Most fluid lava (flood – pahoehoe)	Medium fluidity (pahoehoe – aa)	Most viscous (block)
Thickness of flows	<10 to 100 m	<10 m	10 to 100 m
Areal extent	100 to >100,000 km^2 (distal) Tend to pond; may not thin away from source.	1 to 1000 km^2 (distal to proximal)	1 to 10 km^2 (central) Least tend to pond. Tend to be thicker near or at source.
Ratio: thickness/extent	~1/100 to 1/1000	~1/10 to 1/100	~1/2 to 1/10
Relation to topography	Tend to follow configuration of terrain; drain away from source along depressions (up to 100 km for flood basalts); and tend to bury pre-existing topography.		May not fill depressions and may overlap margins. Peripherally located with respect to source; flows less than 10 km from source. Form topographic highs.
Areal shape	Intricately lobate sheet to elongated tongue.	Similar to most fluid lava.	Tabular, oval, steep-sided dome (coulee).
Flow edge Steepness of flow front, where not bounded by topographic high, is inverse to fluidity.	Low; may be nearly flat with flow thinning gradually to zero thickness.	Low, blunt, with increasing height and steepness for stiffest aa flow.	Thins abruptly at edge. Steep, high wall-like front.

Block lava flows are composed of mafic to silicic lavas that were erupted as stiff, pasty masses mantled by blocks up to several meters in diameter. The flows are generally small in areal extent. Concentric ridges normal to the flow direction generally underlie the blocky veneer (Fig. 4-3(d)). Longitudinal fractures extend radially from the apparent vent. Flow margins of block lavas, in contrast to aa and pahoehoe flows, are smooth and do not necessarily coincide with the adjacent or underlying topography.

The characteristics of lava flow cross sections are shown in Fig. 4-4.

SUBAQUEOUS AND INTRAGLACIAL DEPOSITS

Subaqueous volcanic complexes may form from either eruptive vents that are beneath water, or from lava flows that enter water (Holcomb *et al.*, 1974). The resulting structure is often pod-shaped and resembles block lava flows (Fig. 4-5). Subaqueous basaltic lavas cool into distinctive forms termed *pillow lavas* (Fig. 4-6).

Intraglacial volcanic complexes are also generally pod-shaped structures that cooled from lava erupted beneath ice. They are generally flat-topped structures (termed *tuya*) that resemble block lava flows. However, the lava of intraglacial complexes may have a more uniform surface than block lava flows.

LAHARS (MUDFLOWS)

Lahars, or volcanic mudflows, are fragmental deposits of volcanic rock that are mobilized by water. The water that generates lahars may be derived from crater lakes, heavy rains, or sudden thaws of snow and ice (often resulting from heat generated by eruptions). Lahars generated on volcanic flanks or summits descend valleys, often at very high velocities, and can cover hundreds of square kilometers. Lahars from more than one valley may coalesce in lowlands to form broad deposits (Fig. 4-7).

Active lahars often "pile up" at constrictions in valleys, then are lowered by drainage after the main surge of the flow has passed. Consequently, levees and high flow lines are often left on the slopes of the valleys. In the lower parts of lahars, water from the last stages of the active flow tends to erode and incise the deposits of the lahar.

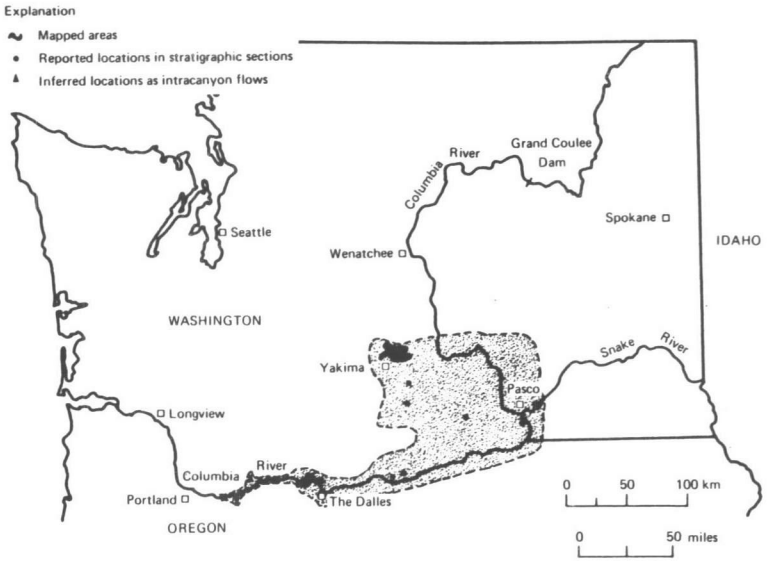


Fig. 4-1. Distribution of a typical flood lava flow, the Pomona Basalt in the Columbia Plateau.

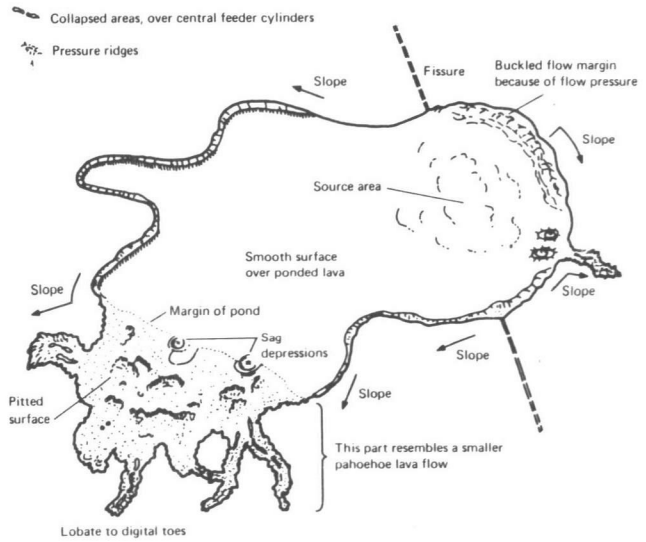
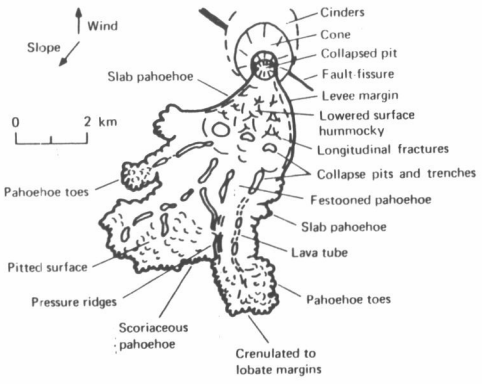
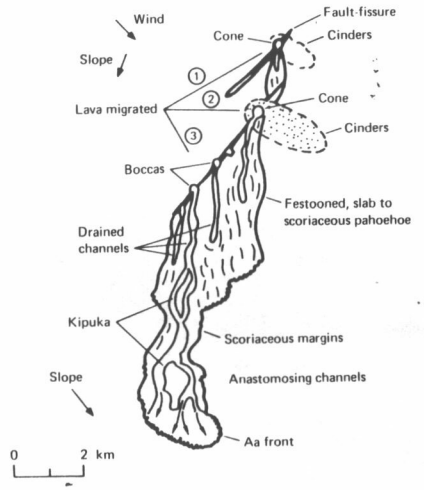


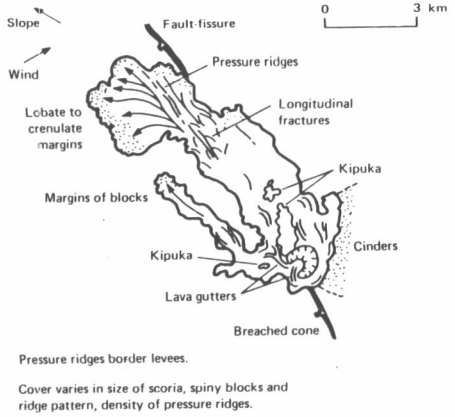
Fig. 4-2. Diagram of a hypothetical flood lava flow derived from a fissure, showing its areal extent (about 100,000 km^2) and typical surface features.



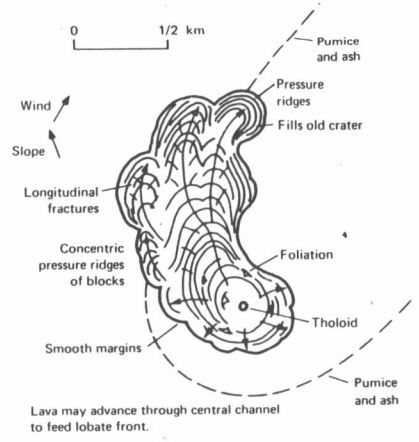
(a) Pahoehoe lava flow on $<2^{\circ}$ slope (Devil's Garden, central Oregon).



(b) Pahoehoe lava flow on $>5^{\circ}$ slope (southwest rift zone, Mauna Loa Volcano, Hawaii).



(c) Aa lava flow on about 2° slope (Mokst Butte, central Oregon).



(d) Block lava flow on about 2° slope (Big Obsidian Flow, central Oregon).

Fig. 4-3. Examples of lava flows showing their areal distribution and surface features.

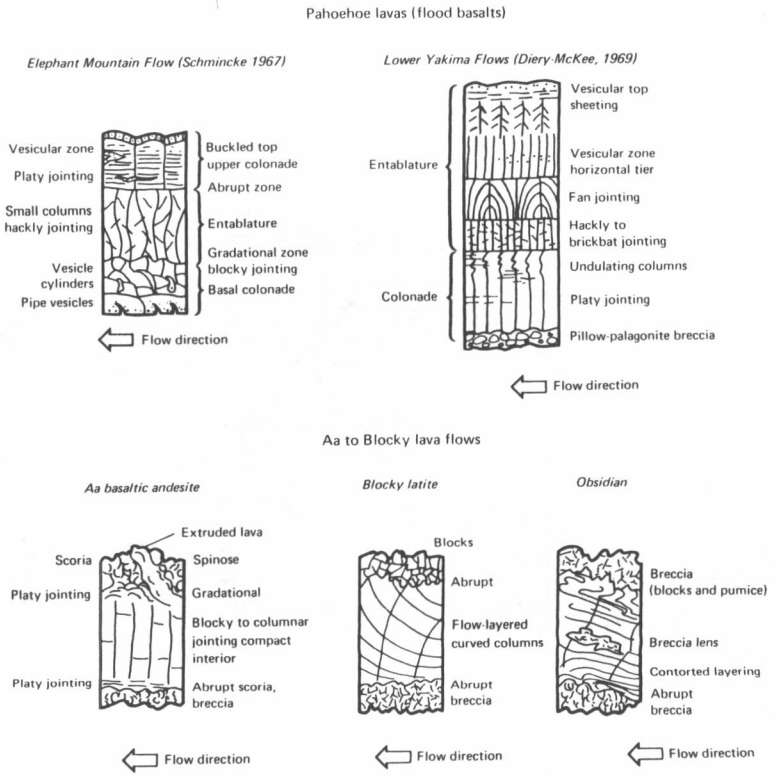


Fig. 4-4. Cross sectional features of lava flows.

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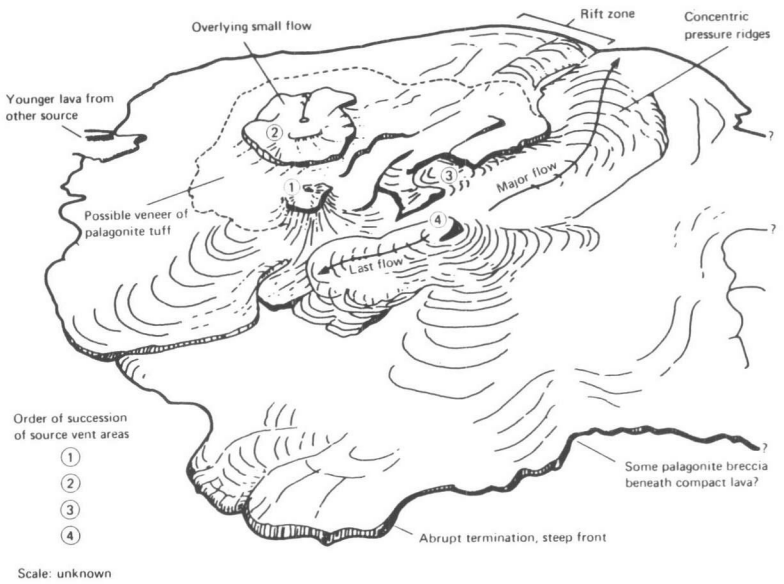

Fig. 4-5. Diagram showing the areal extent and surface features of a subaqueous (marine) pod complex. Feature is in the Danakil Depression, Ethiopia; note the similarity to a block lava flow. *(Drawn from a photograph in National Geographic, vol. 143, no. 1, Jan. 1973.*

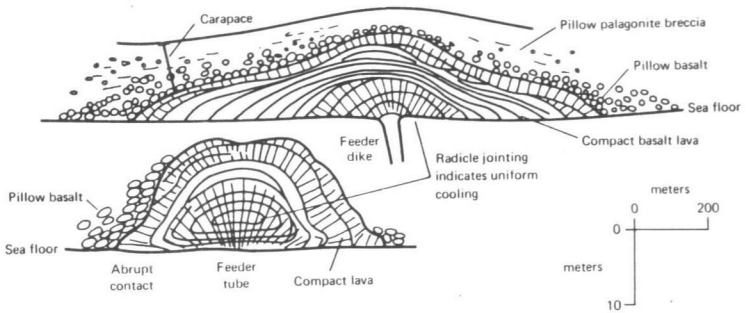

Fig. 4-6. Simplified cross sections of a subaqueous (marine) pod complex in the Coast Range of Oregon.

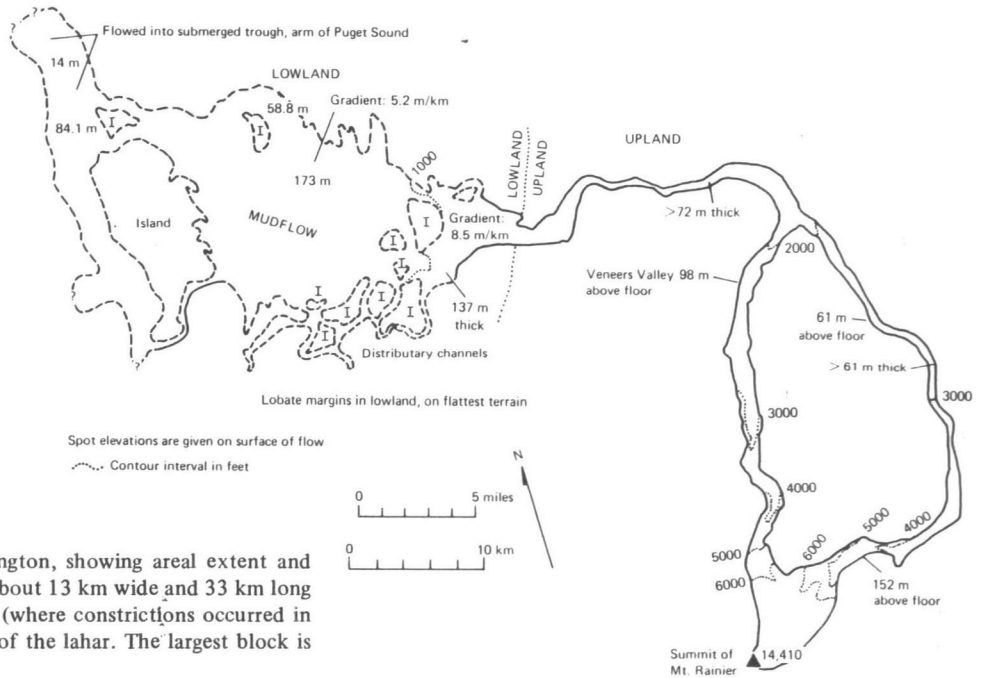

Fig. 4-7. Diagram of the Osceola Mudflow, Mount Rainier, Washington, showing areal extent and surface features (*after Crandell, 1972*). The flow formed a lobe about 13 km wide and 33 km long which ranges in thickness from about 1 m to more than 100 m (where constrictions occurred in narrow valleys). About 30 blocks occur in the "lowland" part of the lahar. The largest block is about 9 m by 12 m.

Lahars have smooth surfaces dotted by boulders of various sizes that were carried down with the flow. The surface may have broad swells and depressions that result from differential compaction of the deposits. Figure 4-8 shows some of the features of lahars in cross section.

DEBRIS AVALANCHE DEPOSITS

Debris avalanche deposits consist of poorly sorted fragmental volcanic rock. They result from accumulations of debris around volcanic vents. The debris becomes unstable, either through earthquakes or explosive heaving of the volcano, and slides downslope. On viscous dome lavas, the upward-pushing dome or plug both fragments the rock and dislodges it, thus generating debris avalanches. The deposits are of small volume and are found both on the flanks of volcanoes and at their bases. The slope of the volcano is generally left smooth. Irregular-shaped pressure ridges occur at the base, and parallel longitudinal ridges occur at the summit. The margins of debris avalanche deposits thin abruptly and do not necessarily parallel the adjacent topography. A columnar section of a typical debris avalanche deposit is shown in Fig. 4-9.

Occasionally, debris avalanches flow into streams and transform to lahars. With increased eruptive activity (i.e., explosions that produce gas-charged particles), the deposits can be expanded into pyroclastic flows.

PYROCLASTIC FLOW DEPOSITS

Pyroclastic flows are produced by continuous explosive activity that produces gas-charged particles of all sizes. These particles sweep down the volcano sides into adjacent valleys, often completely encircling the volcano. Examples are shown in Figs. 4-10 and 4-11. With increased volume and explosive activity, pyroclastic flows grade into ignimbrite units, and if the particles are sufficiently hot, welding may occur.

Very smooth, boulder-strewn surfaces characterize pyroclastic flows; however,there are fewer boulders than in debris avalanche units and the boulders are smaller. The margins of the flow conform to the surrounding topography; if terminated on plains, pyroclastic flow margins are broadly lobate.

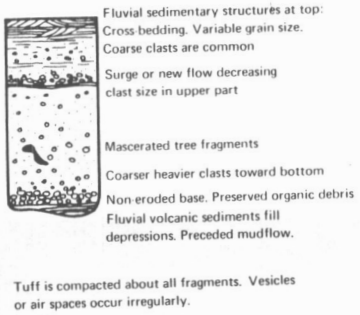

Fig. 4-8. Columnar section of typical lahar, or mudflow deposits.

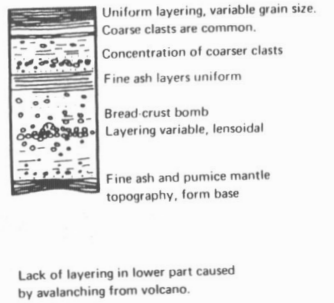

Fig. 4-9. Columnar section of a typical debris avalanche deposit. Pyroclastic flow deposits are similar.

Fig. 4-10. Distribution of the pyroclastic flow in the Valley of Ten Thousand Smokes, Alaska *(after Curtis, 1968)*. The flow has a maximum thickness of about 200 to 275 m and total volume of about 11 km^3. The flow has a very smooth surface and thins to a feather-edge to the northwest, away from the vent. The margins are confined mostly by valley walls.

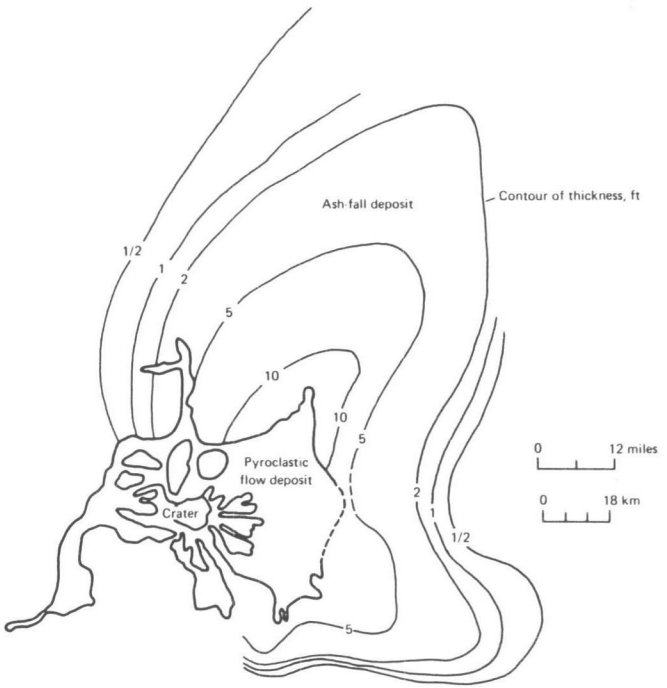

Fig. 4-11. Distribution of pumice flow (pyroclastic flow) and ash-fall deposits at Mount Mazama (Crater Lake), Oregon *(after Williams, 1942)*. The pyroclastic flow extended about 56.4 km from the source. and where not confined by canyons, it spread laterally as a sheet. Pumice bombs up to 4 m in diameter occur on the surface of the flow. Total volume is about 33 km^3. The ash-fall extends north more than 970 km, east more than 800 km, and covers about 900,000 km^2 with a total estimated volume of 38 km^3.

IGNIMBRITES OR ASH FLOW DEPOSITS

Ignimbrites, along with flood lava flows and ash-falls, form the most extensive volcanic units. Ignimbrites result from extremely violent eruptions, termed *nueé ardentes*, in which large quantities of fine-grained, gas-charged particles and gases are rapidly extruded. The erupted mass (Fig. 4-12) flows great distances from the vent and generally follows the terrain along topographic lows. However, flows can also ride up and over topographic obstructions.

Common internal features of ignimbrites are shown in Fig. 4-13. Ignimbrite flow surfaces are similar to pyroclastic flow surfaces, but have fewer boulders.

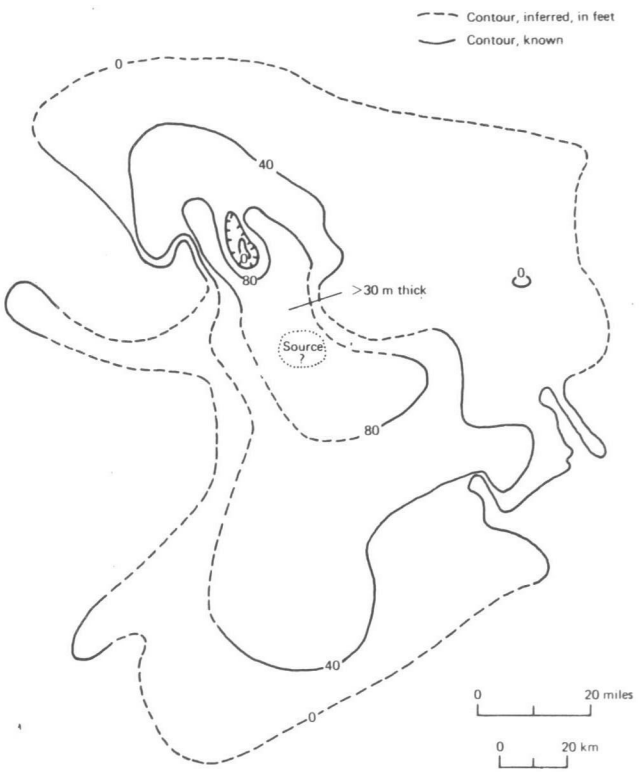

Fig. 4-12. Areal extent and thicknesses of an ignimbrite deposit of Devine Canyon, southeast Oregon *(after Greene, 1973)*. Total area covered is about 18,600 km^2 with a total volume of more than 195 km^3.

ASH–FALL DEPOSITS

Ash-fall deposits are composed of fine-grained volcanic rock that is carried aloft during eruptions and then laterally by the wind, later to settle on the surface. They constitute by far the most extensive volcanic units, but are the most difficult to recognize on aerial photographs because they are so thin that they simply mantle the underlying topography, rather than form distinctive structures. The pattern of their distribution is determined mostly by the strength and direction of the wind at the time of eruption. A constant wind from one direction produces a narrow, cigar-shaped pattern that extends downwind from the vent (Greeley, 1974, Fig. 25). Changes in the wind direction can produce bilobed (Fig. 4-11) or multiple-lobed patterns. If no wind is blowing at the time of eruption, the ash settles around the volcano in a circular pattern.

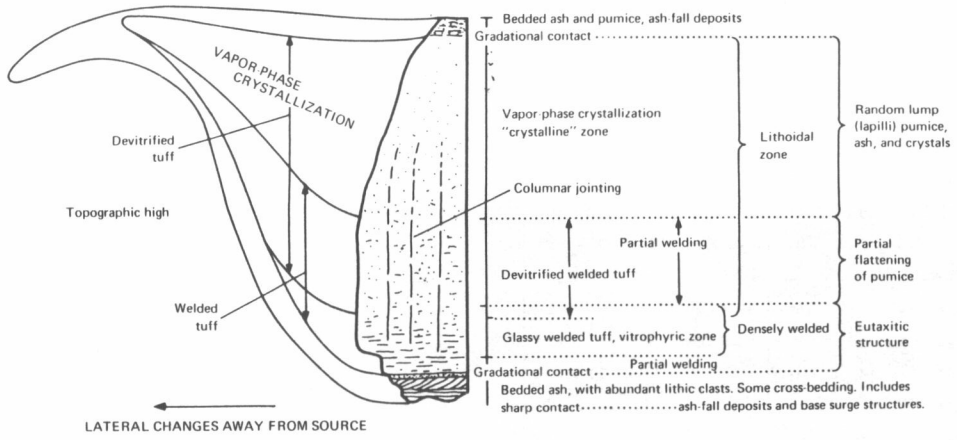

Fig. 4-13. Diagram and columnar section showing zoning in an ignimbrite deposit.

Much of the ash produced during eruptions is carried to very high altitudes and is distributed far from the volcano, eventually settling to the ground where it mixes with other sediments. Thus, the recognizable ash-fall deposit may represent only a small fraction of the total ash produced.

AERIAL IDENTIFICATION

A comparison of the areal extent and configuration of the 10 volcanic stratigraphic units described here (Table 4-1) shows that at least three general types can be distinguished from the air, or on aerial photographs: (1) lava flows; (2) fragmental deposits (lahars, debris avalanche deposits, pyroclastic flow deposits, ash flow units); and (3) ash-fall deposits. Observations at very low altitudes (or large-scale photographs) would be required to differentiate types of units within one of the three groups since their recognition depends primarily on fine-scale surface textures. At high altitudes (or small-scale photographs), only units of great areal extent could be recognized, such as flood lava flows, ignimbrites, and ash-fall units.

Ash-fall deposits can be distinguished by the light color of the ash-mantled terrain and the distribution pattern in relation to known, or suspected, vents. Flood lavas and ignimbrites can be distinguished by the features tabulated below:

Feature	Flood Lavas	Ignimbrites
Color	Dark	Light
Surface of Deposit	Locally smooth, pitted and furrowed near margins.	Smooth throughout its extent
Margin	Irregular, intricately lobate to digital.	Broadly lobate

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5. RECENT LANDFORMS AT KILAUEA VOLCANO
A Selected Photographic Compilation

Robin T. Holcomb, Donald W. Peterson,
Robert I. Tilling
United States Geological Survey
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Recent eruptive activity at Kilauea has produced great changes in the landscape, modifying old landforms and creating new ones. Some of these landforms are observed fairly commonly in basaltic terrains, but many had rarely, if ever, been observed before in the process of development. The 1969-74 Mauna Ulu eruptions have provided the first historic opportunity at Kilauea to witness and record the development of features associated with flank activity of long duration. The photographs of new or modified landforms in this compilation place special emphasis on possible extraterrestrial analogs.

CHANGES ALONG RIFT ZONES

Kilauea's upper east rift zone is characterized by a chain of several pit craters and a set of en echelon fissures trending east-northeast. The copious lava produced during rift eruptions since 1963 has tended to bury pit craters and pre-existing fissures, while new fissures and cones have formed. Changes along the upper east rift zone are illustrated in Fig. 5-1.

In contrast to the long-lasting eruptions on the upper east rift zone, a short eruption in September 1971 on the upper southwest rift zone produced thin flows that only partly masked pre-existing features, and distinct new fissures developed (Fig. 5-2).

CHANGES AT MAUNA ULU

Beginning in 1969, localization of activity in the upper east rift zone resulted in the growth of a new basaltic shield, Mauna Ulu (Swanson *et al.*, 1971). Several selected stages of Mauna Ulu's development are shown in Figs. 5-3 to 5-6.

ENCLOSED LAVA PONDS

Several types of lava ponds have formed at Kilauea during recent activity. Some of these ponds formed during short eruptions involving high volume rates of eruption, originating from fountain-fed flows (Swanson, 1973). Examples are those formed in 1973 at Pauahi and Hiiaka (Figs. 5-7 and 5-8). Both ponds partly drained at the end of the eruptions, leaving lava-subsidence terraces on the crater walls. A different type of confined flow was produced in the summit caldera on August 14, 1971, when lava was erupted rapidly from fissures within Kilauea caldera (Fig. 5-9), flowed laterally away from the eruptive vents and pond in the low part of the caldera floor. Although the lava pond did not drain into fissures at the end of the eruption, a prominent marginal lava-subsidence terrace shows that the surface of the flow subsided markedly, in part the result of spreading of the flow, but probably chiefly the result of deflation by escaping gas.

PERCHED LAVA PONDS

In contrast to the enclosed lava ponds produced during high-rate eruptions, other ponds have formed during low-rate eruptive periods. These ponds are here termed *perched lava ponds*, examples of which are shown in Fig. 5-10. Perching is caused by the ponding of lava behind natural levees and may be caused by several different mechanisms, illustrated and briefly explained in the photographs (Figs. 5-10 and 5-16).

UNCONFINED LAVA FLOWS

Recent activity spawned many lava flows that moved great distances from the eruptive vent without ponding. Characteristics of both aa and pahoehoe flows are illustrated in Figs. 5-17 to 5-20. Swanson (1973) and Greeley (1971, 1972) have described some of the processes in greater detail.

DEVELOPMENT OF LAVA–TUBE SYSTEMS

Long-lived eruptions at Mauna Ulu from 1970 to 1973 resulted in the development of several lava-tube systems. Lava streams developed roofs by a variety of processes (Figs. 5-21 to 5-24), which are discussed in greater detail by Greeley (1971,1972), Cruikshank and Wood (1972), and Peterson and Swanson (1974).

TALUS–AND–LAVA CONES

When a lava stream cascades over a steep cliff, a characteristic landform, here termed *talus-and-lava cone*, sometimes develops at the base. Talus-and-lava cones were produced in the western pit of Makaopuhi Crater in 1972; Figs. 5-25 and 5-26 show their development. Talus-and-lava cones are not restricted to pit craters, however, as they are common along fault scarps on the south flank of Kilauea.

SUBSURFACE FILLING OF A PIT CRATER

During 1972 a lava tube system was extended over the high crater walls of Makaopuhi, through the talus-and-lava cones, and beneath the surface crust on the lava pond in the crater. Lava fed through this tube system accumulated below the crust under a great hydrostatic load, and the crust gradually rose piston-like several tens of meters as lava entered the lake. Figures 5-27 and 5-31 show the sequence of events during the filling of Makaopuhi's western pit.

LAVA DELTAS

Several times from 1970 to 1973, lava-tube systems delivered pahoehoe lava to the ocean, 12 km from the eruptive vents. When lava encounters the sea, a variety of processes ensue, and when the flow persists, a lava delta is formed. Some of the processes and results are illustrated in Figs. 5-32 to 5-38, and they are discussed in more detail by Moore *et al.* (1973), and Peterson (in press).

Fig. 5-1. Changes caused by the Mauna Ulu eruption in the area from Aloi to Makaopuhi Craters.

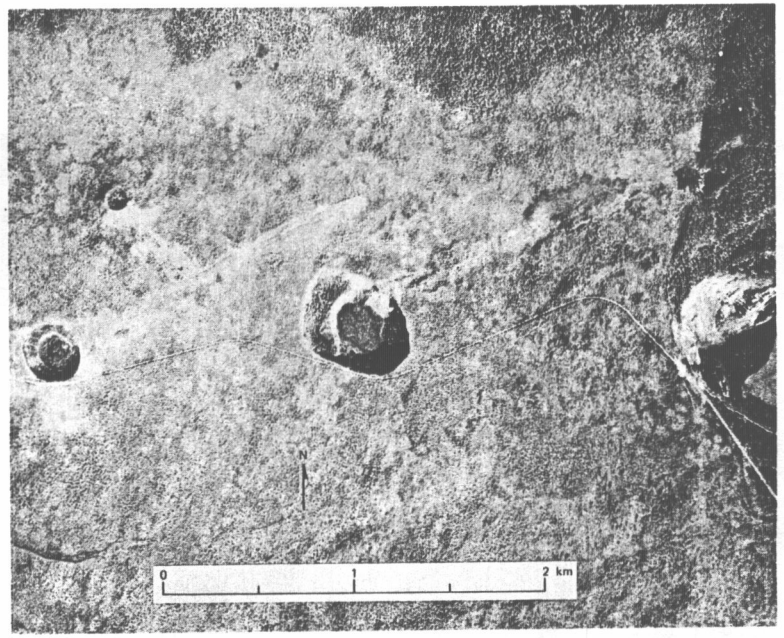

Fig. 5-1A. Aerial view prior to the Mauna Ulu eruption, north at top. Alae Crater is at the center, Aloi Crater at the left, and the west pit of Makaopuhi Crater at the right. Puu Huluhulu, a prehistoric spatter and lava cone with a summit crater, is north-northeast of Aloi. The prominent lineament extending east-northeastward from Aloi Crater is a zone of fissures from which an eruption issued in December 1965 and upon which Mauna Ulu grew, beginning in May 1969. Other eruptions have issued from along and parallel to the zone of fissures extending east-northeastward from Alae Crater. In this view Aloi, Alae, and Makaopuhi contain lava erupted in the twentieth century. (*Photo: U. S. Department of Agriculture, February 1965.*)

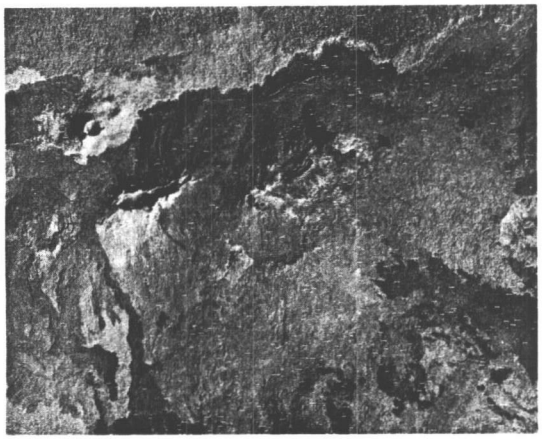

Fig. 5-1B. The same region in July 1973, after lava flows from Mauna Ulu covered most of the area. The Mauna Ulu lava shield grew between Aloi and Alae Craters; its summit is indented by an elongated crater. Puu Huluhulu is unchanged except for its southern base, which is covered with lava. The west pit of Makaopuhi Crater has been filled. Alae Crater was filled and has been covered by a low lava shield; a shallow depression reflects the outline of the former crater. Aloi Crater has also been buried, and a small, irregular subsided area approximates its former site. (*Photo: R. M. Towill Corporation, July 21, 1973.*)

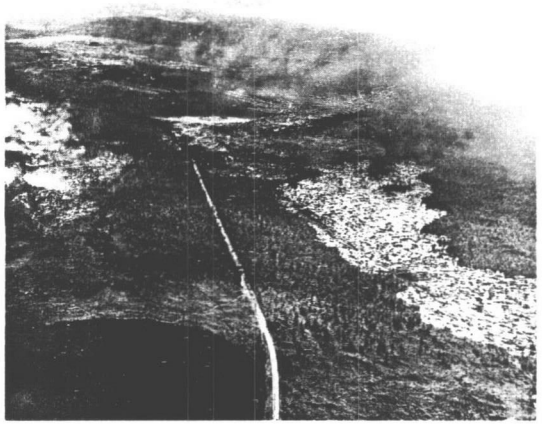

Figure 5-1C. Eastward view along the east rift zone of Kilauea following eruption of February 1969. Aloi Crater is in the left foreground, beyond are Alae and Kane Nui o Hamo, a hill just north of Makaopuhi. Fresh lava has been extruded from en echelon fissures. Sulfurous fume rises from fissures of December 1965 eruption near left edge of photograph. (*Photograph by D. W. Reeser, National Park Service, March 18, 1969.*)

Fig. 5-2. Changes caused by 1971 eruptive activity along the upper southwest rift of Kilauea near the southwest margin of the caldera.

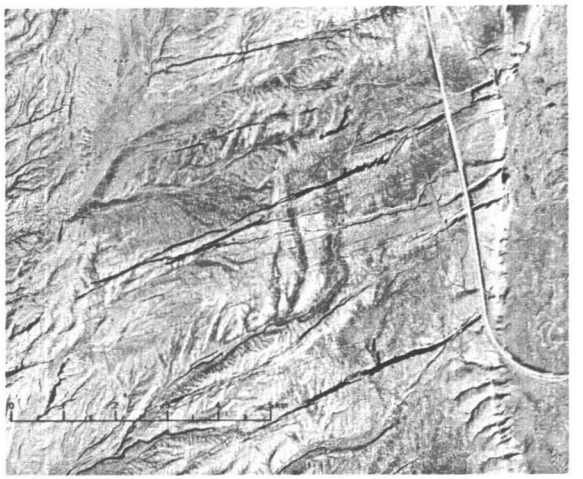

Fig. 5-2A. Pre-eruption view. The caldera margin is on the right, crossed by Crater Rim Drive; caldera-related faults also are seen near left edge of photograph. Subparallel gaping fissures, small cracks, and graben extend southwestward along the rift zone. (*Photo: U. S. Department of Agriculture, 1965.*)

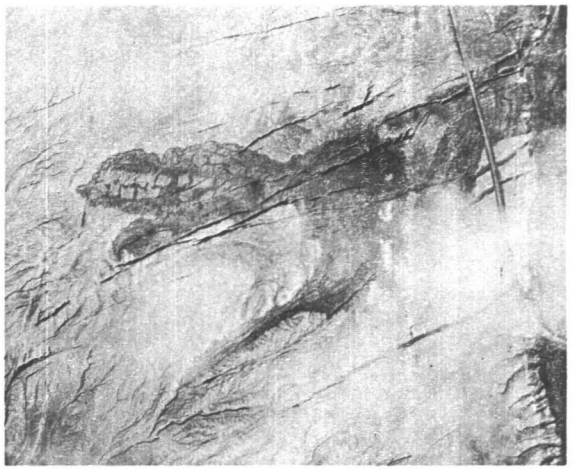

Fig. 5-2B. The same field of view showing lava flows erupted on September 24, 1971. Some new cracks developed and some pre-existing cracks widened during the eruption. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

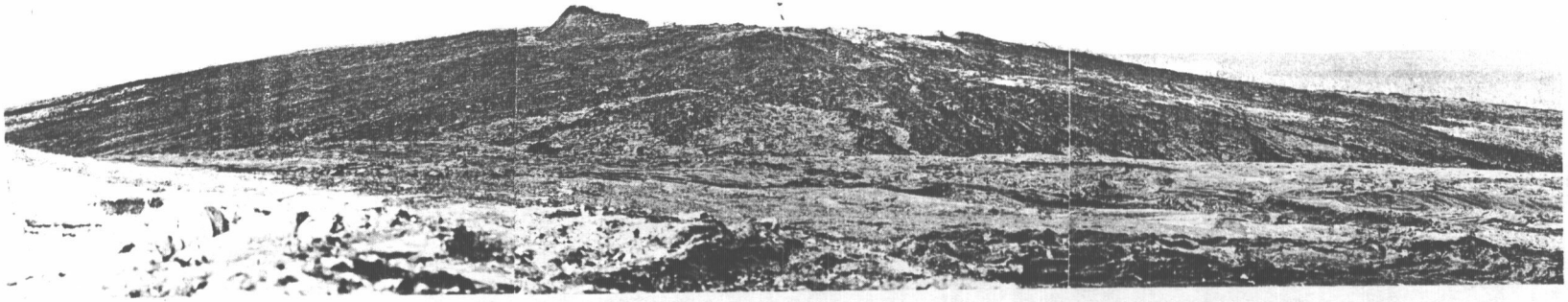

Fig. 5-3A. Profile of the Mauna Ulu lava shield as seen from Alae. The shield of Mauna Loa Volcano looms in the background. (*Photo: R. T. Holcomb, U.S.G.S., February 6, 1972.*)

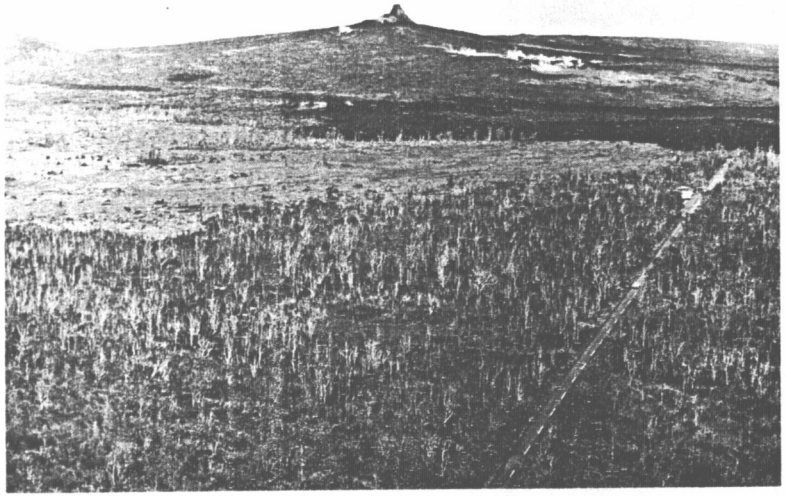

Fig. 5-3B. Aerial view of the Mauna Ulu lava shield from the west. A steep-sided spatter cone tops the summit. Puu Huluhulu is at the left; the lava shield of Alae is behind and to the right of Mauna Ulu. (*Photo: R. I. Tilling, U.S.G.S., March 27, 1974.*)

Fig. 5-4. Development of the summit crater at Mauna Ulu.

Fig. 5-4A. Collapsing walls of the Mauna Ulu vent have produced a crater about 30 m wide (left-to-right) and 70 m long. A remnant of an earlier spatter cone is on the far edge; a partly collapsed lava tube is in left foreground. View is northeastward. (*Photo: R. Greeley, NASA, August 1970.*)

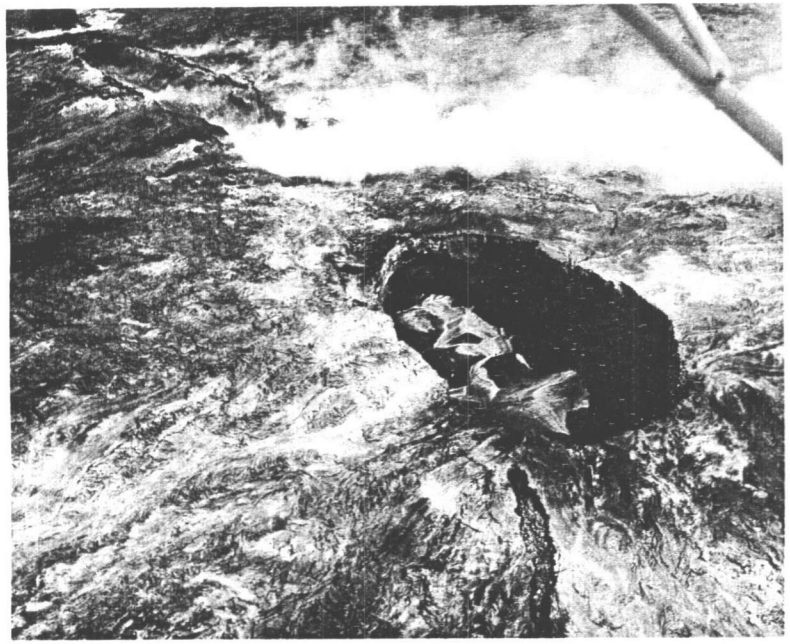

Fig. 5-4B. Eastward view of growing crater. Marginal spatter cone and part of collapsed lava tube (remnant in foreground) have disappeared; enlarged crater with dimensions approximately 90 by 160 m is occupied by a lava lake. Additional collapse to the northeastward has formed a linear trench, beyond which is a small circular pit (upper left). (*Photo: W. A. Duffield, U.S.G.S., late February 1971.*)

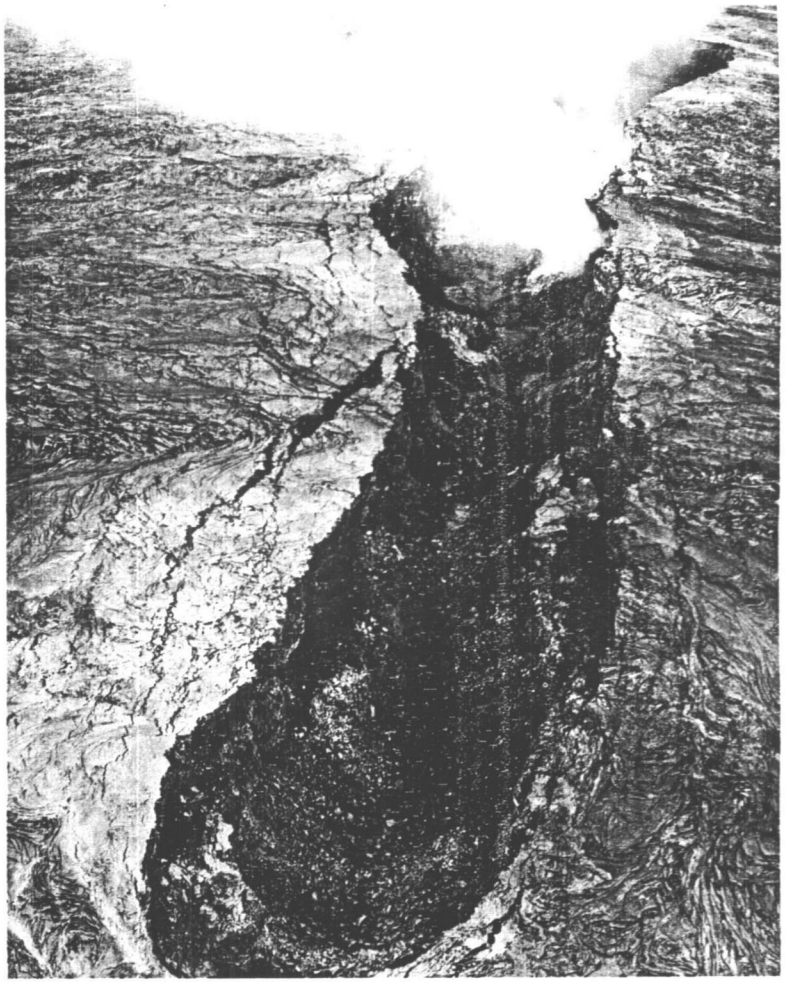

Fig. 5-4C. Southwestward view along the trench toward the summit crater of Mauna Ulu. As collapse of walls continued, the crater and trench merged. Large cracks have formed behind the blocks slumping into the trench. (*Photo: W. A. Duffield, U.S.G.S., September 14, 1972.*)

Fig. 5-5. Lava lake activity in summit crater of Mauna Ulu.

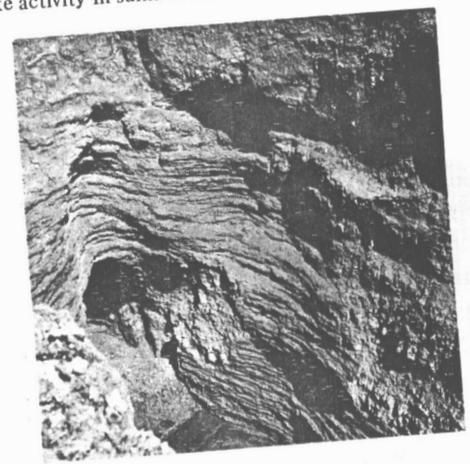

Fig. 5-5A. Crater with lake at a low level. Lake surface is visible in lower center, approximately 150 m below the rim. Rugose veneer remained plastered on crater walls in some places, but has mostly fallen away. Part of a vertical dike is visible against far wall of grotto. (*Photo: D. W. Peterson, U.S.G.S., August 1971.*)

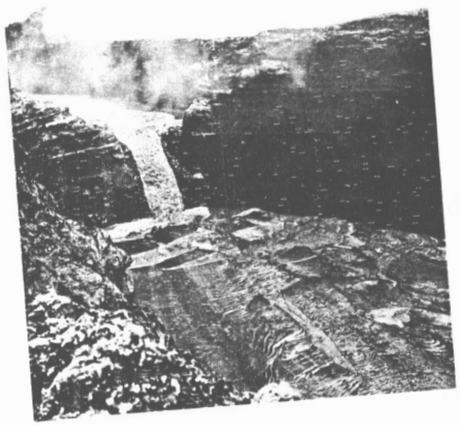

Fig. 5-5B. A septum divides the main crater of Mauna Ulu from the trench, and lava lakes occupy both compartments. Lake levels fluctuated independently, and at this time lava, at a higher level in the eastern compartment, was overflowing into the western compartment in falls approximately 20 m high. (*Photo: D. W. Peterson, U.S.G.S., March 5, 1972.*)

Fig. 5-5C. A lava lake rising within the crater of Mauna Ulu is circulating from the foreground toward the background. A stationary island in the middle of the lake leaves a "wake" in the thinly crusted lake surface. Terrace-like structures high on the crater wall mark earlier stands of lava. (*Photo: D. W. Peterson, U.S.G.S., June 9, 1973.*)

Fig. 5-5D. Crater of Mauna Ulu is nearly filled with lava following a period of overflow and shield growth. The circular structure in the background is the shallow depression over Alae Crater. (*Photo: W. A. Duffield, U.S.G.S., March 17, 1972.*)

Fig. 5-6. Vertical views of changes at Mauna Ulu.

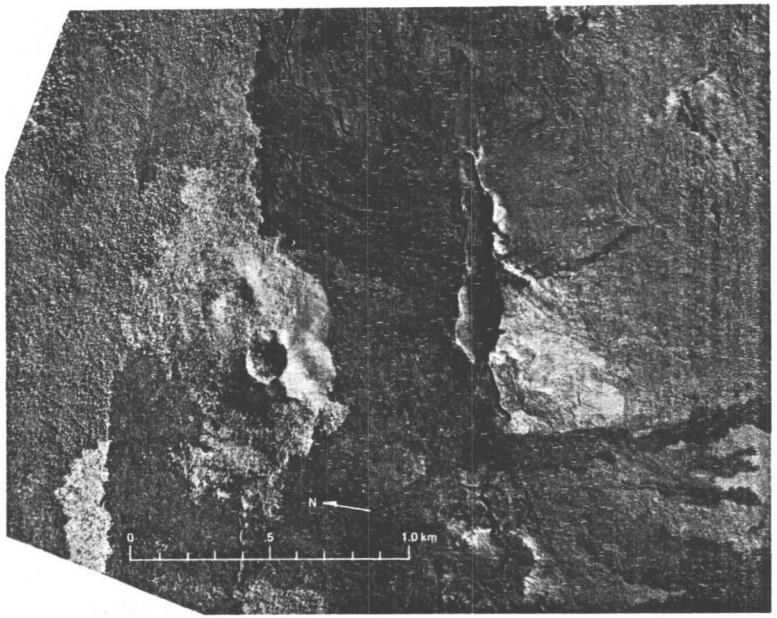

Fig. 5-6A. Crater at Mauna Ulu after progressive collapse of walls; crater measures about 100 m by 700 m. Note slump structures in the spatter mantle of Puu Huluhulu. (*Photo: R. M. Towill Corporation, July 21, 1973.*)

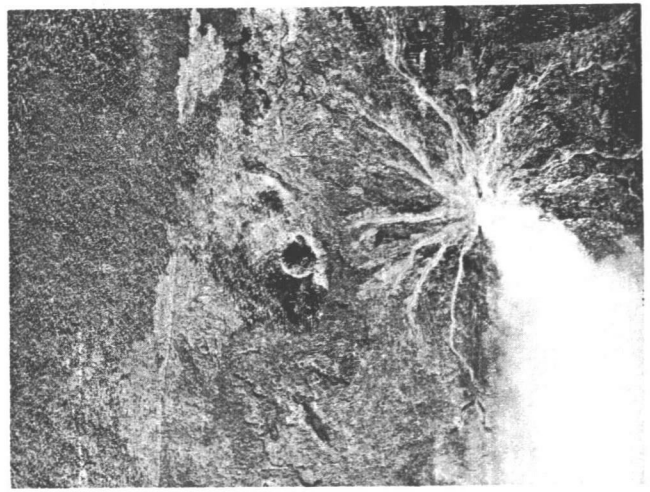

Fig. 5-6B. Mauna Ulu during copious overflow. Radiating spokes are large streams of lava, and Mauna Ulu is nearly covered with molten lava. Only the eastern end of the former crater is visible. A lava pond has formed in the saddle between Mauna Ulu and Puu Huluhulu, impounded by a lava levee facing Puu Huluhulu. Slump structures on Puu Huluhulu have been covered by lava. (*Photo: R. M. Towill Corporation, June 1, 1974.*)

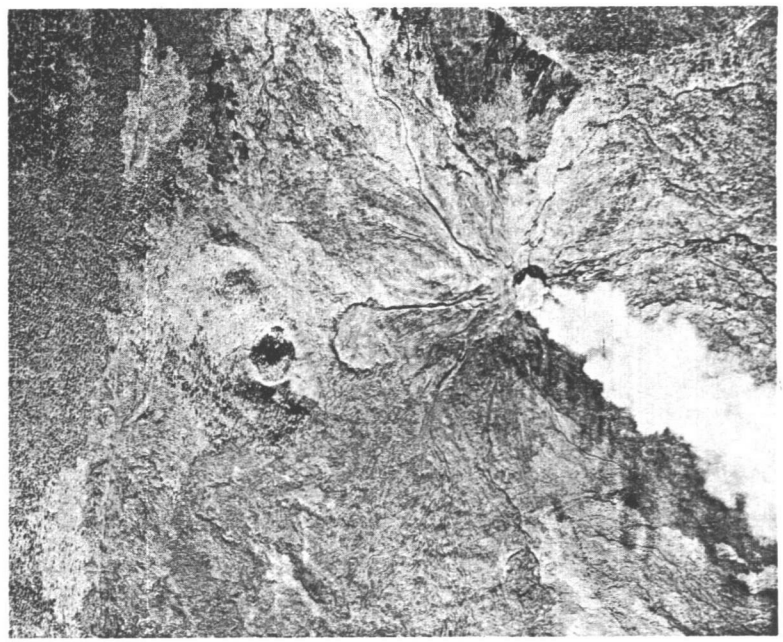

Fig. 5-6C. Mauna Ulu after the overflow episode. Radiating channels are empty of lava, and the surface of the pond between Mauna Ulu and Puu Huluhulu has subsided. The crater is about 40 m in diameter. (*Photo: R. M. Towill Corporation, June 3, 1974.*)

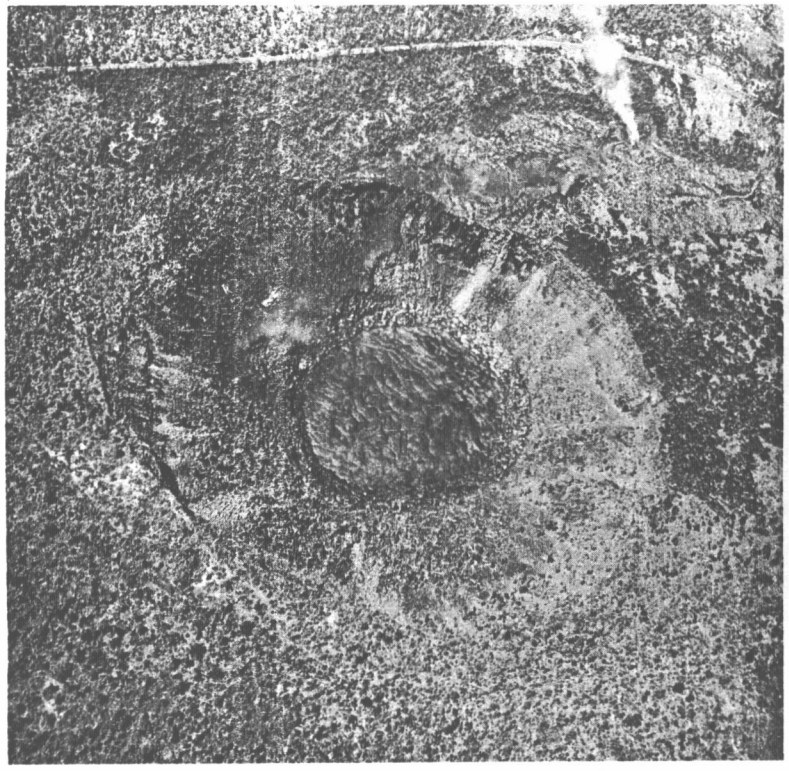

Fig. 5-7. Hiiaka Crater after the eruption of May 5, 1973. A flat-surfaced lava pond is ringed by a lava-subsidence terrace, a rind of lava plastered to the talus mantling the lower crater walls. The top of the terrace marks the highest stand of the lava lake during the eruption; in the late stages of the eruption, the lake partly drained into a fissure. (*Photo: R. T. Holcomb, U.S.G.S., May 6, 1973.*)

Fig. 5-8. Sequence showing changes at Pauahi Crater resulting from eruptive activity in 1972. (*Photo: W. W. Dunmire, National Park Service, July, 1961.*)

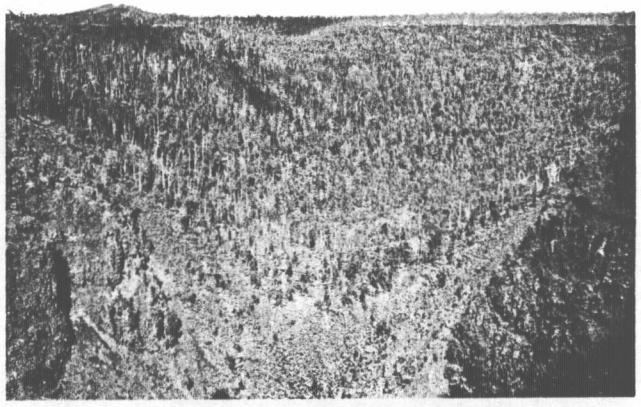

Fig. 5-8A. View eastward across Pauahi, as it appeared before the 1973 eruptions. The septum separating the east and west pits is about 100 m below the rim of the crater. (*Photo: W. W. Dunmire, National Park Service, July 1961.*)

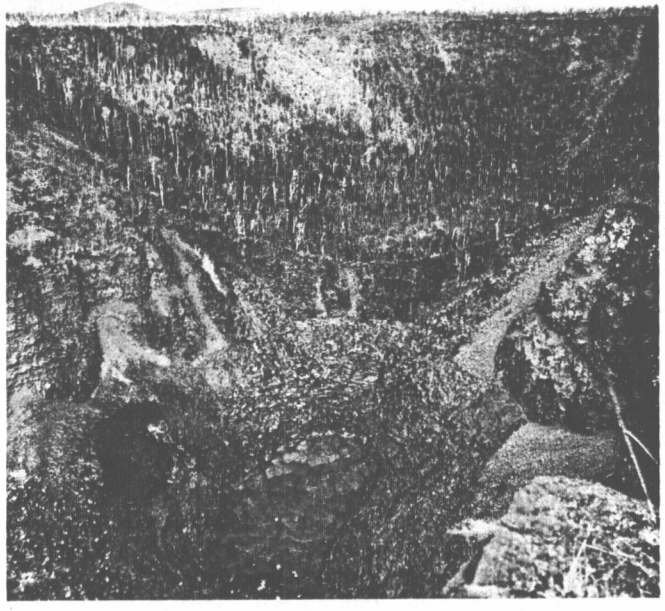

Fig. 5-8B. View eastward across Pauahi after the eruption of May 5, 1973. A lava lake filled the deep west pit of Pauahi nearly to the level of the top of the septum, then subsided to leave a lava-subsidence terrace. (*Photo: R. T. Holcomb, U.S.G.S., May 1973.*)

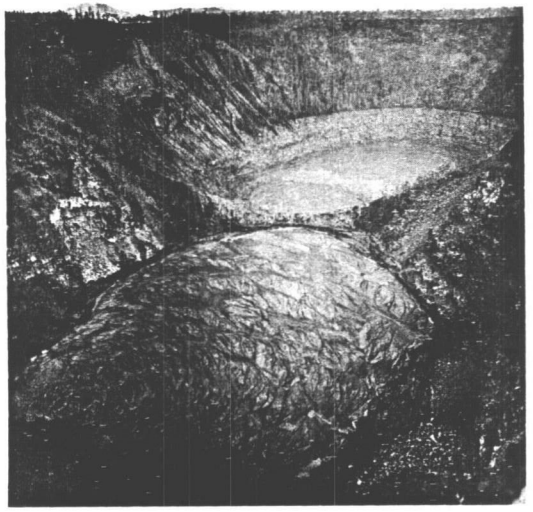

Fig. 5-8C. View eastward across Pauahi; lava lake in the east pit has subsided after partly draining into fissures. The eruptive fissure of November 10-11 extends up the north wall toward Puu Huluhulu, the cone in the left background. Continued eruptive activity has almost filled the west pit with a lava lake. (*Photo: D. W. Peterson, U.S.G.S., November 15, 1973.*)

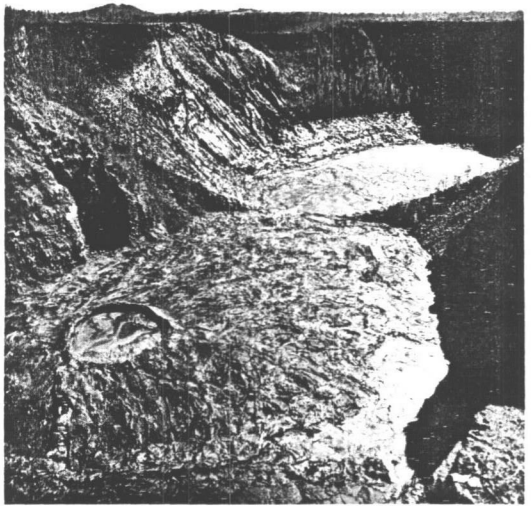

Fig. 5-8D. Continued eruption in Pauahi's west pit has built a low lava shield. A small crater in the summit of the shield contains a pond of molten lava. A small amount of lava has flowed across the septum into the eastern pit. (*Photo: R. T. Holcomb, U.S.G.S., December 5, 1973.*)

Fig. 5-9. Ponded lava flow in Kilauea Caldera August 14, 1971.

Fig. 5-9A. Lava is fountaining from en echelon fissures on the south part of the floor of the caldera. Another fissure on the rim of the caldera to the left stopped erupting shortly before this photo was taken. The fountains are feeding copious streams of lava flowing northeastward (left). (*Photo: W. A. Duffield, U.S.G.S., August 14, 1971.*)

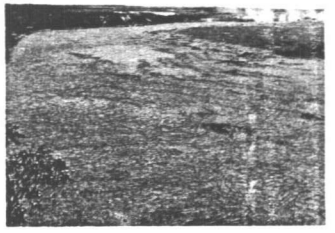

Fig. 5-9B. View southwestward of the ponded lava flow after activity ended. Vents, upper right, continue to emit fume. A lava-subsidence terrace has formed along the base of the caldera wall. "Islands," center right, appear to have formed above preexisting tumuli on the caldera floor. (*Photo: D. W. Peterson, U.S.G.S., August 27, 1971.*)

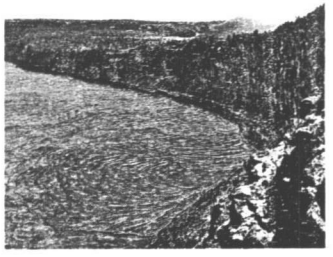

Fig. 5-9C. Subsided surface of the lava pond, showing details. Conspicuous flow fronts indicate lava that oozed out over the previously solidified and partly foundered crust during subsidence of the surface; some of them lap up on the lava-subsidence terrace. Puu Puai, upper right, is a pumice and agglutinate deposit formed by the 1959 Kilauea Iki eruption. (*Photo: D. W. Peterson, U.S.G.S., August 27, 1971.*)

Fig. 5-10. Historic and recent perched lava ponds (ponds confined by self-constructed levees so that the surface of lava is higher than surrounding terrain).

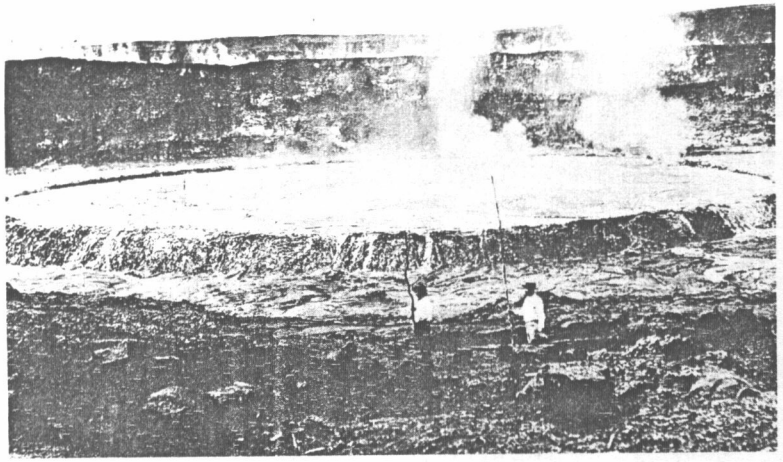

Fig. 5-10A. A perched pond in Halemaumau in 1885. (*Photo: National Park Service files.*)

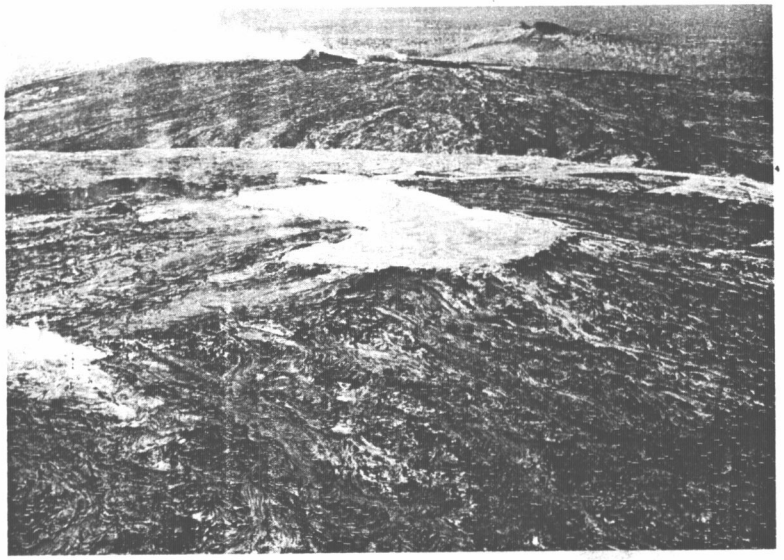

Fig. 5-10B. Lava pond perched at the summit of the shield built over site of Alae Crater. View northwestward toward Mauna Ulu; Puu Huluhulu at upper right. (*Photo: R. I. Tilling, U.S.G.S., September 8, 1972.*)

Fig. 5-11. Development of levees and perched lava ponds.

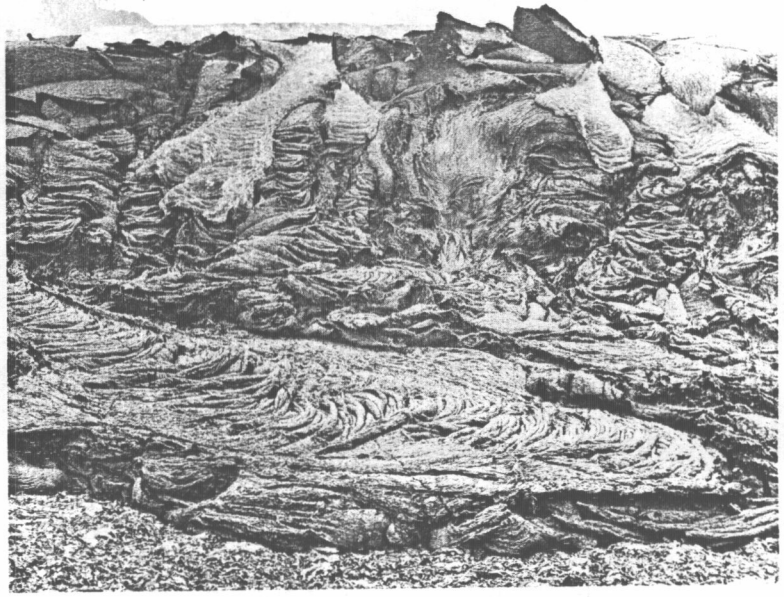

Fig. 5-11A. A rapidly growing levee, 2 m high, Mauna Ulu. Tongues of pahoehoe are overflowing the levee at many points. This levee consists mostly of such tongues, although some plates of crusted lava from the lake surface have been pushed on top of the levee as well. The fountain feeding this lake is at upper left. Figure 16A shows a general view of this perched lake. (*Photo: R. T. Holcomb, U.S.G.S., January 21, 1974.*)

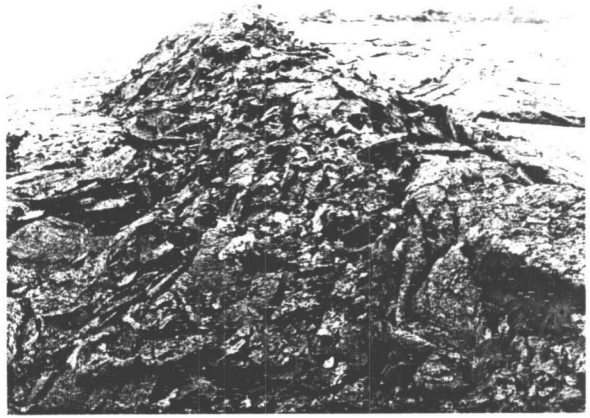

Fig. 5-11B. A slowly growing lava levee, 4 m high, Mauna Ulu. The level of the lava lake has almost stabilized, and levee growth is mainly by the accumulation of plates pushed onto the top by circulating lava. Intermittent small rootless fountains around the lake margin may add a veneer of spatter to the levee. Some levees grow mainly by the accumulation of such spatter. Figure 5-15I shows a general view of this lake. (*Photo: R. T. Holcomb, U.S.G.S., November 9, 1973.*)

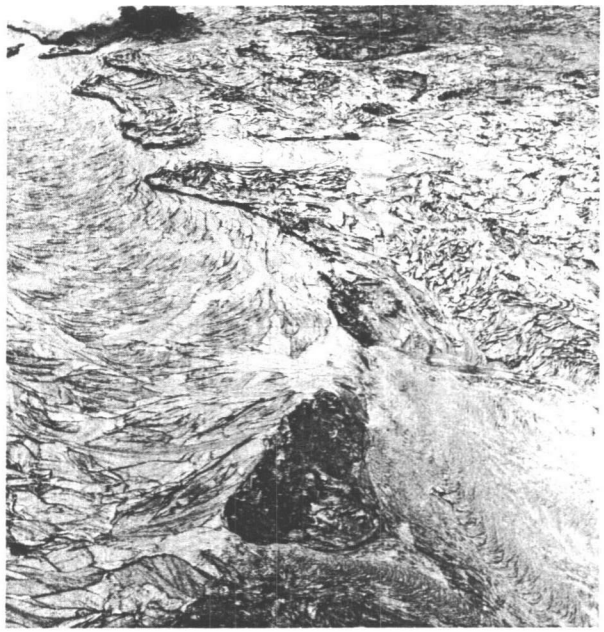

Fig. 5-11C. Lava overflowing levee of the perched pond at Alae. Width of each stream crossing levee is about 5 m. Such overflows are an important process of levee growth, for when the flow stops, the mantle of overflow lava adds to the height and width of the levee. Subsequent overflows occur at other low points, and gradually the height along the entire length of the levee is raised. (*Photo: D. W. Peterson, U.S.G.S., April 23, 1972.*)

Fig. 5-12. Growth of lava shield at site of pit crater.

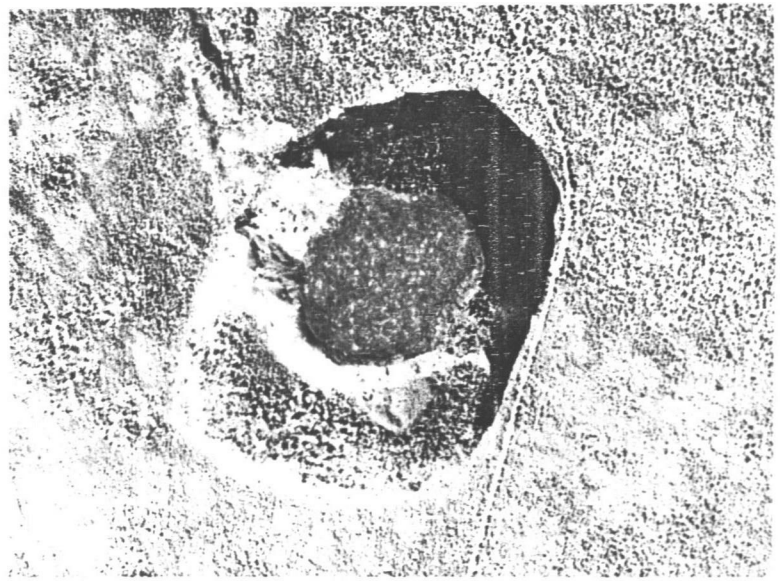

Fig. 5-12A. Alae Crater prior to Mauna Ulu eruption. The enclosed lava pond in the crater formed in 1963. Subsequently, complex events occurred at Alae from 1969 to 1971 and are described by Swanson and others (1972) and Swanson and Peterson (1972); also see figure 5-14. (*Photo: Department of Agriculture, 1965.*)

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Fig. 5-12B. Lava shield that grew in 1972 over the site of the former Alae Crater, center; lava shield of Mauna Ulu, upper left; same view and scale as figure 12A. Perched lava ponds have temporarily subsided to form irregular depressions atop the shield. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

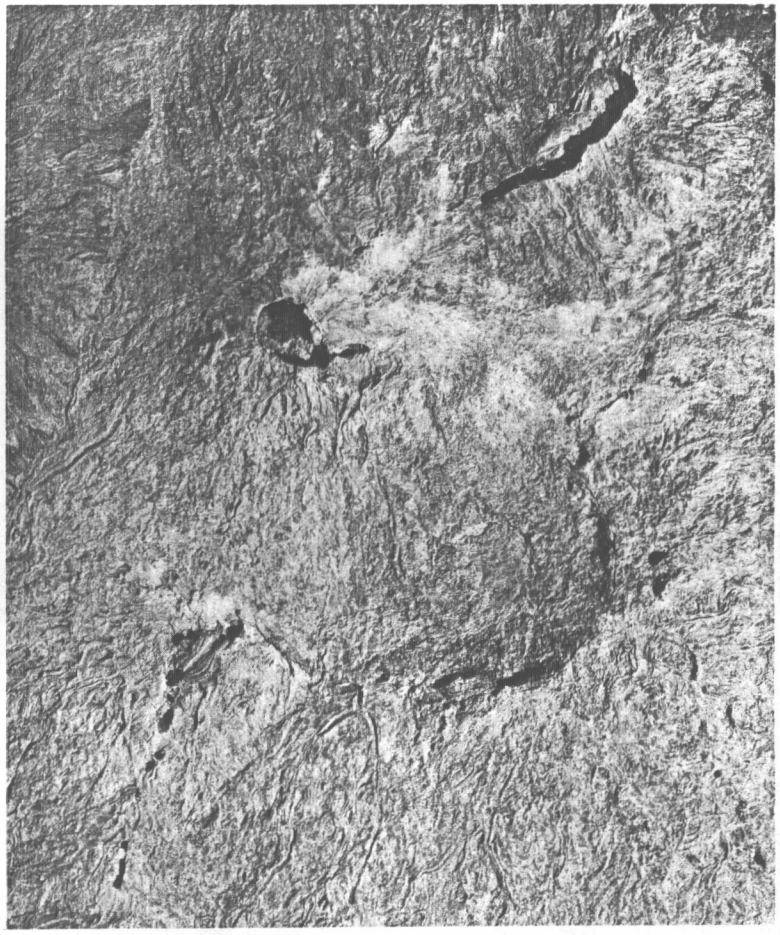


Fig. 5-12C. After eruptive activity ceased at Alae in the spring of 1973, the summit of the new shield gradually subsided, leaving a shallow circular depression roughly indicating the outline of the former pit crater, whose rim is buried under about 60 m of lava. Vent, upper left, was fed by a lava tube from Mauna Ulu. Lava channels and skylights along lava tubes extend toward lower left corner. (*Photo: R. M. Towill Corporation, July 21, 1973.*)

Fig. 5-13. Contraction of the perched pond above Alae Crater.

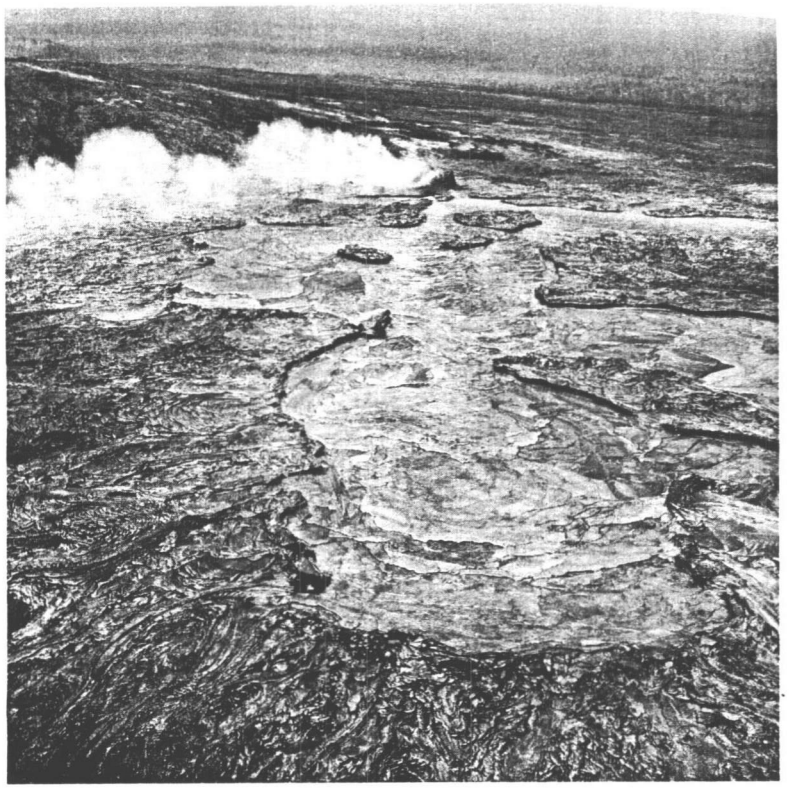


Fig. 5-13A. The 1972 lava pond initially occupied the entire shallow depression above the former crater. As the lava shield grew by repeated overflows, the surface area of the pond gradually decreased by accretion of crust to its margins. Peninsulas and islands developed, further reducing the surface area. (*Photo: D. W. Peterson, U.S.G.S., April 23, 1972.*)

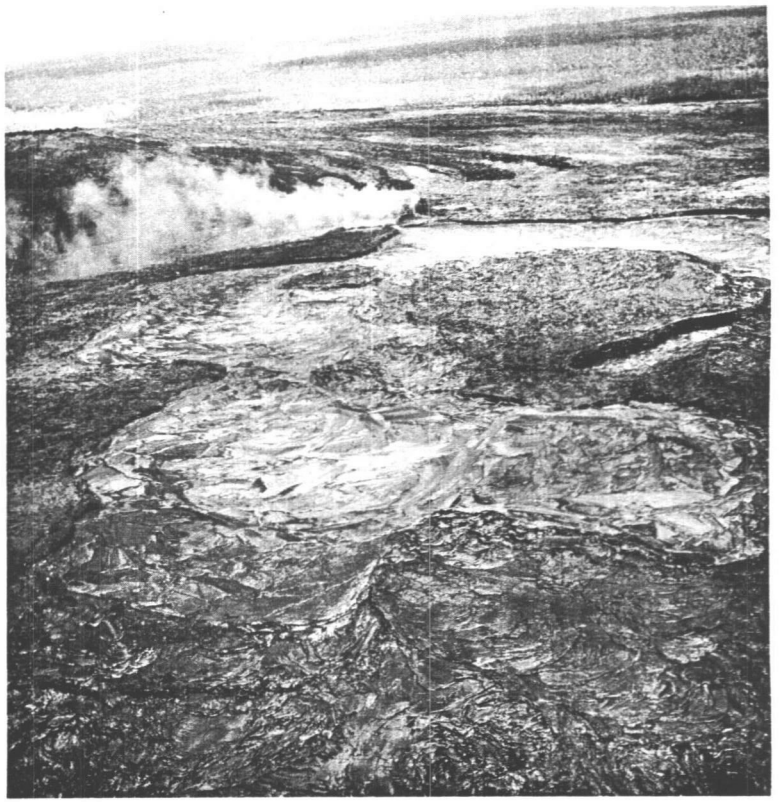


Fig. 5-13B. Continued growth of the lava shield at Alae was accompanied by further contraction of the lake surface. Islands in the center of the lake coalesced forming a peninsula dividing the lake into two main compartments, each of which continued to contract. A smaller pond within the peninsula (center right) was apparently cut off from the other two ponds, indicated by its lower level. (*Photo: D. W. Peterson, U.S.G.S., May 26, 1972.*)

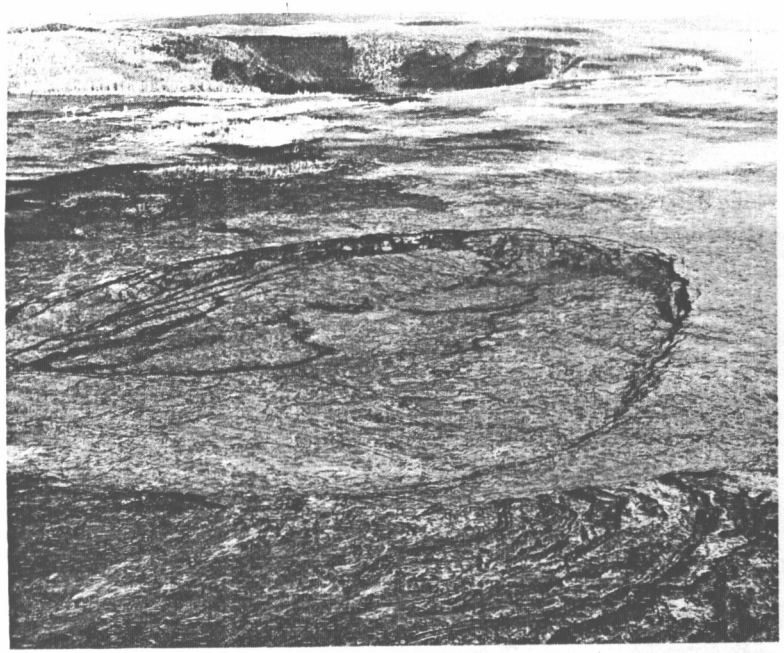


Fig. 5-14. Subsidence depression at Alae after the complex filling and draining episodes of 1969-71 (Swanson and others, 1972) and prior to the persistent lava inflow of 1972 that led to the development of the lava shield and perched pond. The depression is ringed by open tension cracks, whereas the center is occupied by compressional ridges (Swanson and Peterson, 1972). Makaopuhi Crater lies in the background. (*Photo: W. A. Duffield, U.S.G.S., September 14, 1971.*)

Fig. 5-15. Sequence of filling and draining of the summit crater of Mauna Ulu in 1973; all views are eastward from the western end of the crater.

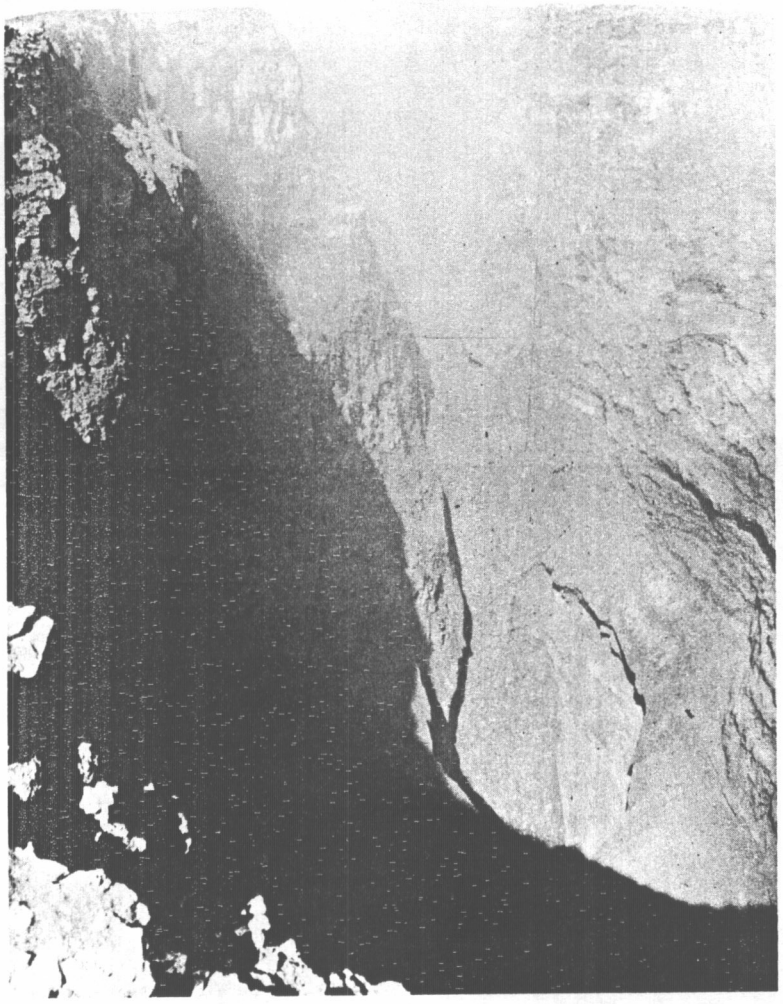


Fig. 5-15A. Summit crater of Mauna Ulu one day after the lava lake completely drained. Figure 4D shows a general view. Crater is approximately 100 m wide and 200 m deep. (*Photo: R. I. Tilling, U.S.G.S., May 6, 1973.*)

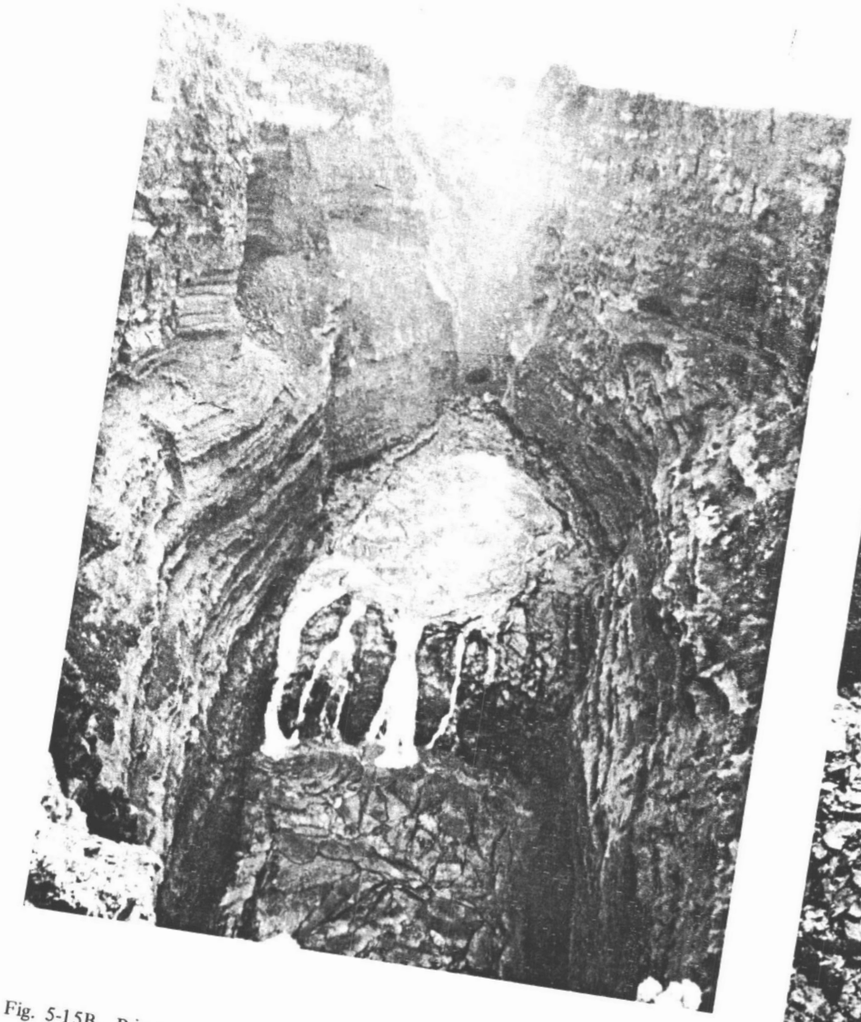


Fig. 5-15B. Renewed eruption has begun to fill the crater. A lava lake in the eastern segment of the crater built a lava levee about 15 m high and is shown here overflowing the levee into the deeper western part of the crater. (*Photo: R. I. Tilling, U.S.G.S., May 18, 1973.*)

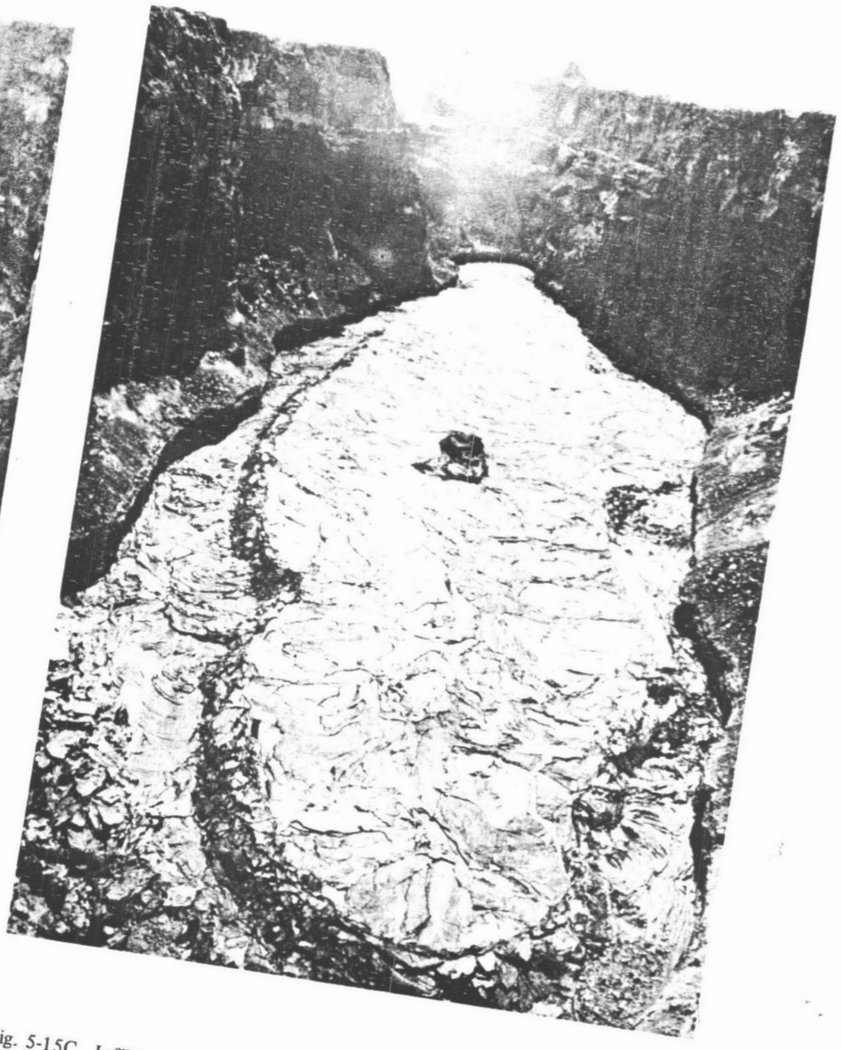


Fig. 5-15C. Infilling continued, and levees confine an inner lake that frequently overflows into the surrounding moat. An island has formed in the center of the lake. (*Photo: R. I. Tilling, U.S.G.S., June 15, 1973.*)

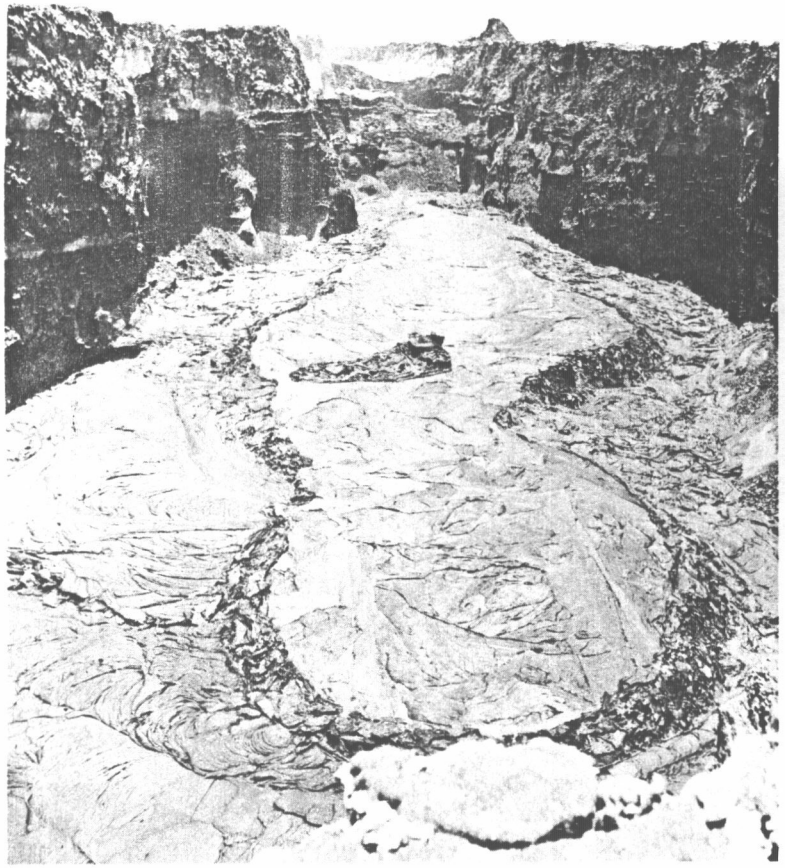


Fig. 5-15D. The surface of the active lake has decreased as the levees grew inward from the crater walls. The island has grown larger. Dominant direction of flow on the lake surface is toward the camera. (*Photo: D. W. Peterson, U.S.G.S., June 21, 1973.*)

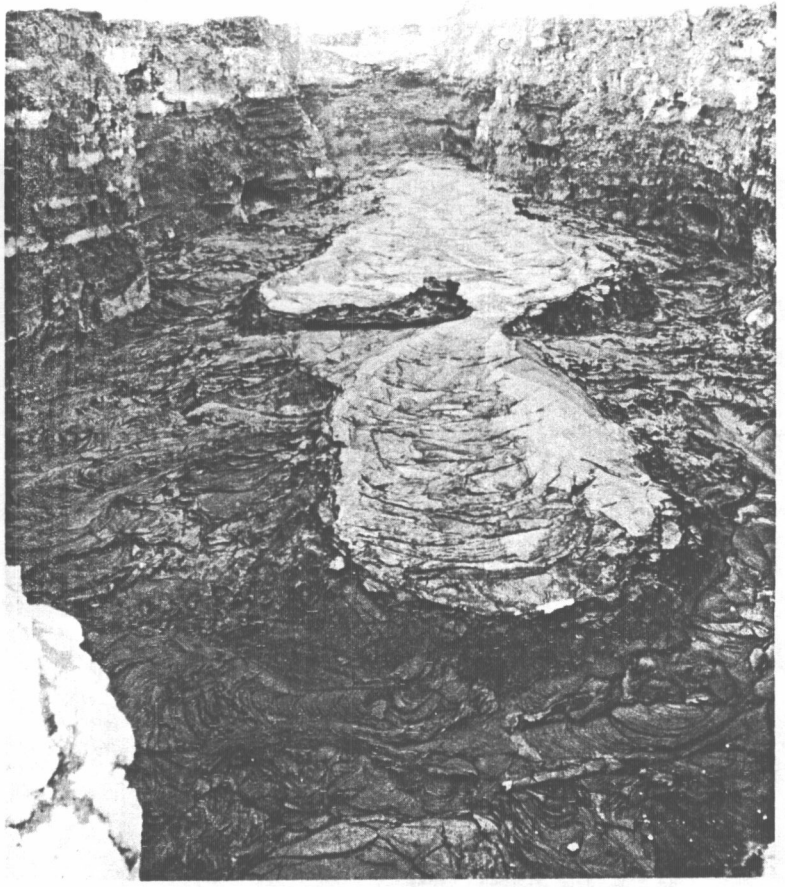


Fig. 5-15E. As the lake level rose, the surface area of the lake continued to decrease. The former island has become a peninsula that nearly separates the lake into two ponds. (*Photo: R. I. Tilling, U.S.G.S., June 24, 1973.*)

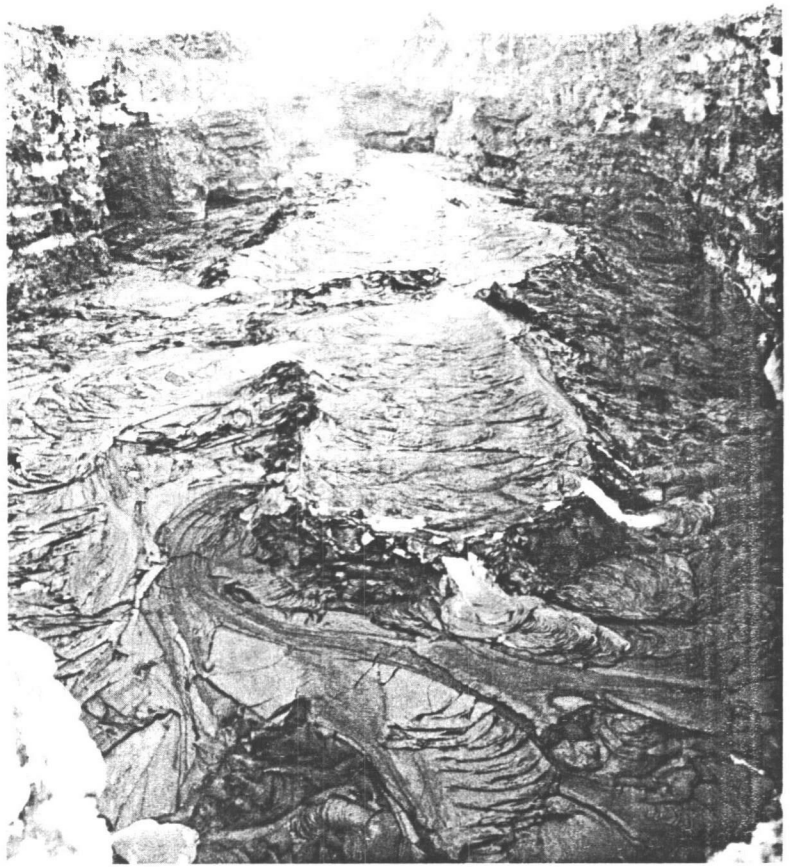


Fig. 5-15F. A rise in the lake surface has flooded the levees with new lava. The marginal crust slopes gently outward from the perched lake to the crater walls. (*Photo: R. I. Tilling, U.S.G.S., June 28, 1973.*)

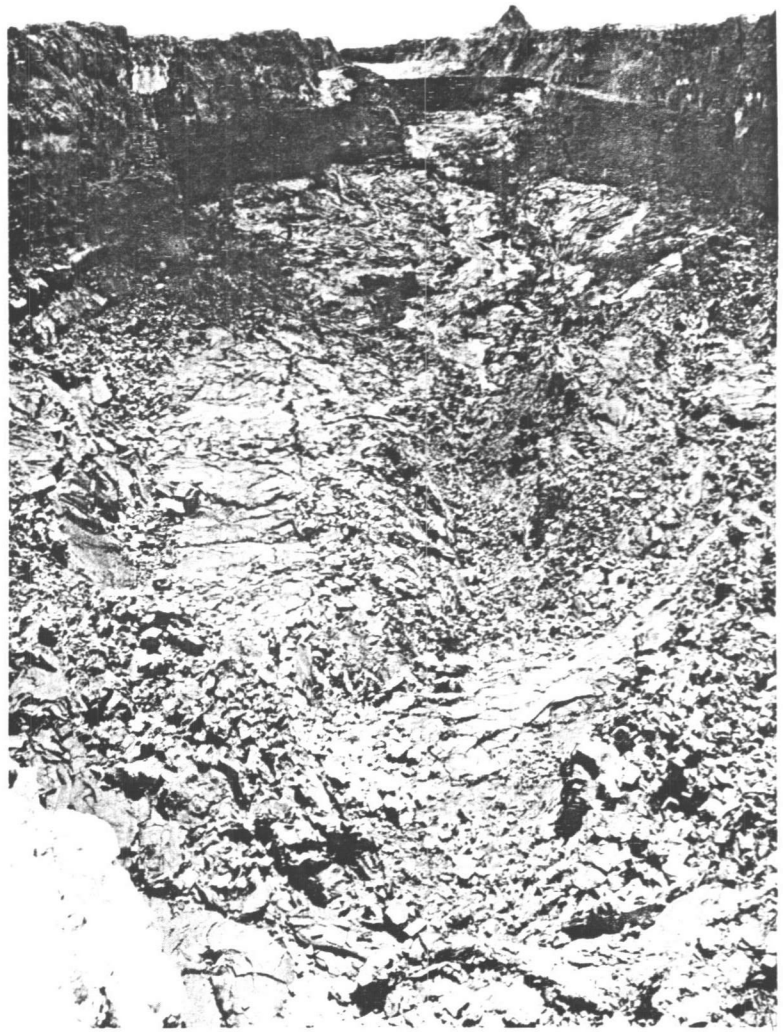


Fig. 5-15G. Draining of the lava caused a collapse of the perched pond and surrounding crust. (*Photo: R. I. Tilling, U.S.G.S., July 25, 1973.*)

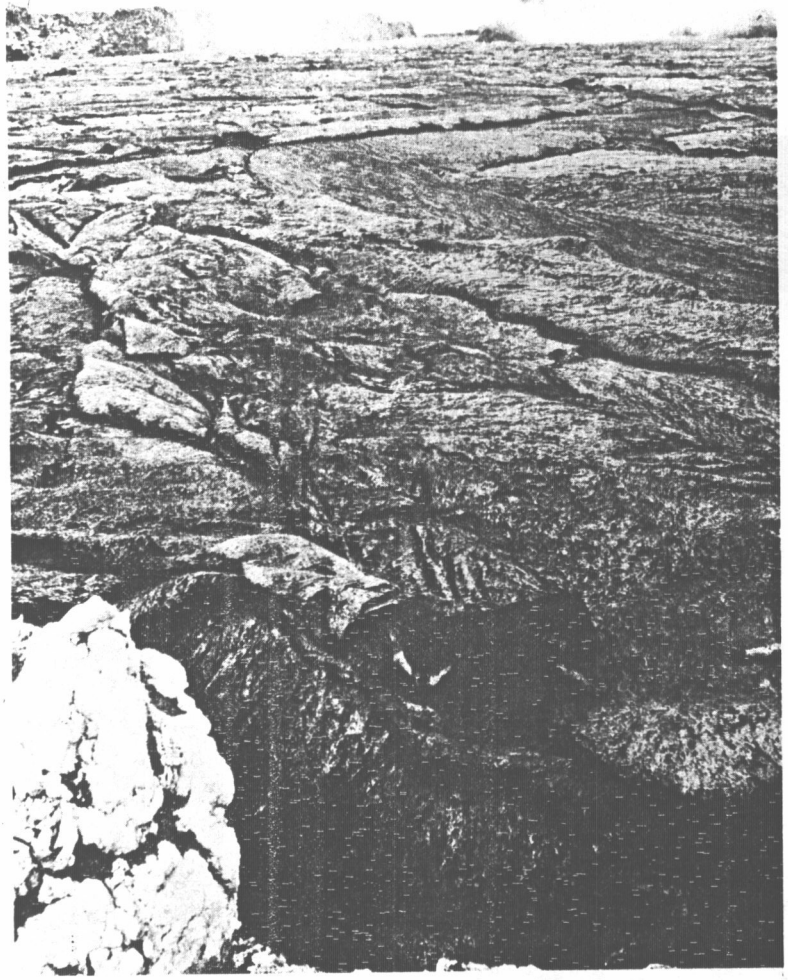


Fig. 5-15H. Rapid filling produced a lava lake without levees. The fountain in the background fed the lake. Viewpoint is same as preceding photos. (*Photo: R. I. Tilling, U.S.G.S., November 4, 1973.*)

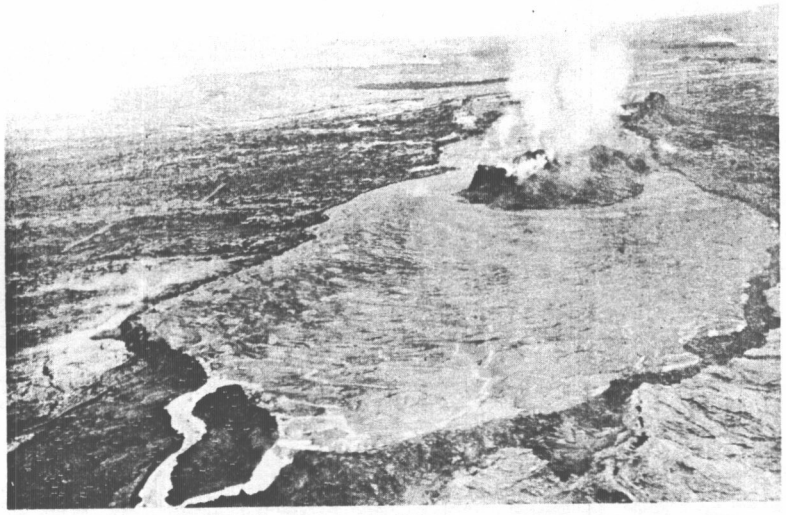


Fig. 5-15I. Continued rise of the Mauna Ulu lava lake resulted in overflow of the summit crater. As the lake level stabilized when overflows began, levees again developed, confining a perched lake at an elevation higher than the initial crater rim. The site from which preceding photographs were taken is in the foreground where the stream on the right overflows the levee. (*Photo: R. I. Tilling, U.S.G.S., November 7, 1973.*)

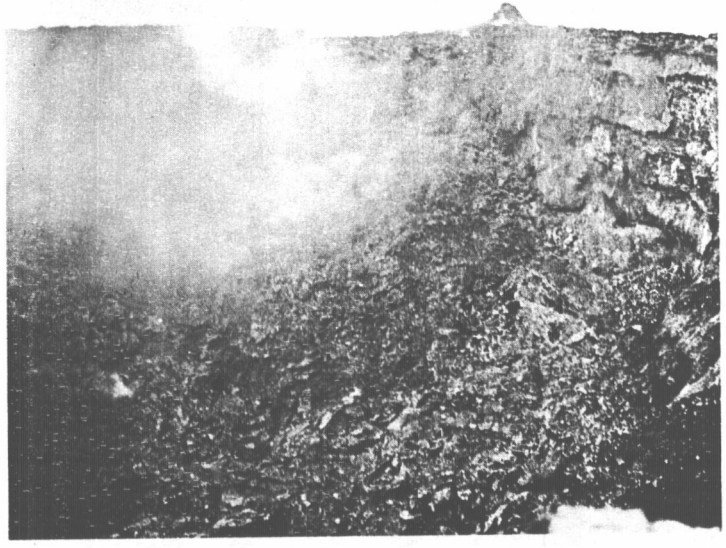


Fig. 5-15J. Rapid draining of lava from Mauna Ulu on November 10 left a rubble-covered crater floor 40 m deep. During the draining, the levees on the rim, left unsupported, collapsed. (*Photo: D. W. Peterson, U.S.G.S., November 12, 1973.*)

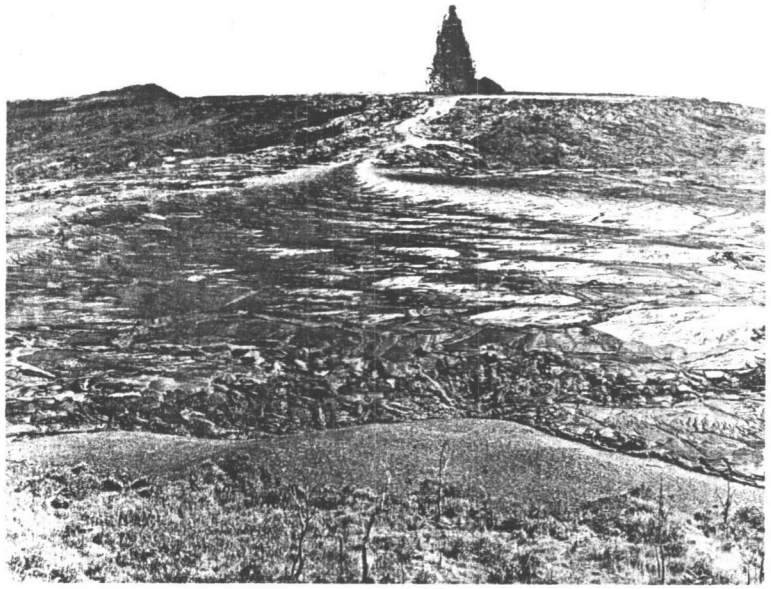


Fig. 5-16A. A crusted lava pond forming in the saddle between Mauna Ulu and Puu Huluhulu, viewed from the summit of Puu Huluhulu. The perched lava lake at the summit of Mauna Ulu, surrounding the vent fountain, overflowed the confining levee. The copious stream is ponding in the saddle area and levees are beginning to form. (*Photo: R. T. Holcomb, U.S.G.S., January 25, 1974.*)

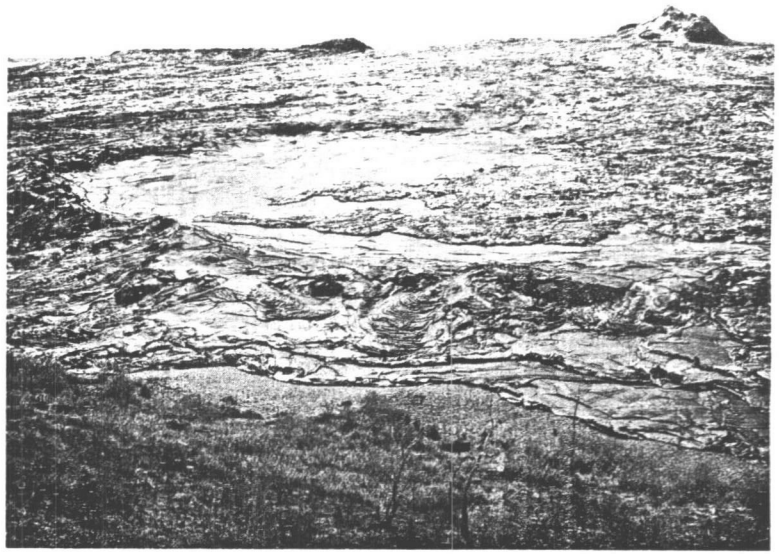


Fig. 5-16B. The same view after several additional episodes of overflow. New lava solidified above the former lava lake at the summit of Mauna Ulu, and the spatter cone at upper right marks the eruptive vent. The surface of the new pond between Mauna Ulu and Puu Huluhulu subsided behind the new levees, and subsequent tongues of pahoehoe extended over the surface. (*Photo: R. T. Holcomb, U.S.G.S., February 25, 1972.*)

Fig. 5-17. Development of aa by remobilization of ponded lava.

Fig. 5-17A. Vertical view of the site of buried Aloi Crater (depression in upper center). The end of the Chain of Craters road shows at upper left. Lava ponding above the site of Aloi in February 1971 was accompanied by massive slow movement of lava from the south side of the pond. Viscosity of the pasty and degassed lava was high, and the movement caused the lava to form aa, which appears here as the dark flow. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

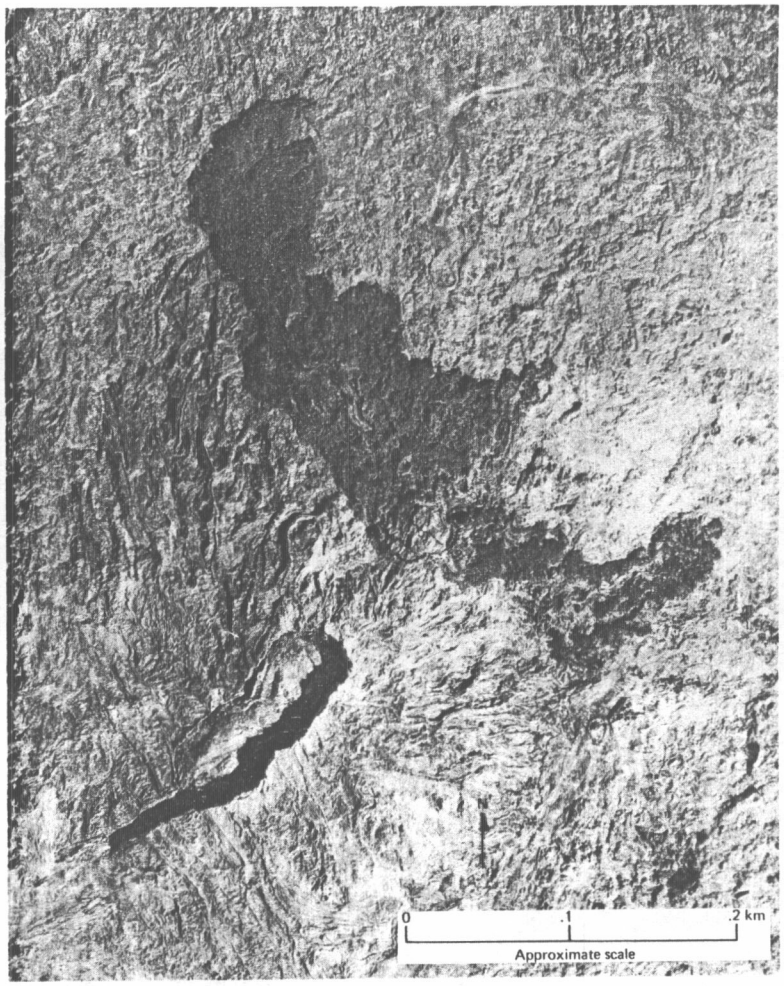


Fig. 5-17B. Vertical view of the northeast flank of lava shield over Alae. During November 1972 a crust developed on a partly ponded accumulation of lava and on associated sluggish overflows. After the crust formed, it began to move along with the viscous underlying lava, and developed two aa flows that moved north and east. The surface later subsided at the site of the pond, and younger pahoehoe partly covered the aa. (*Photo: R. M. Towill Corporation, July 21, 1973.*)

Fig. 5-18. Transition of pahoehoe to aa with increasing distance from eruptive vent (see Swanson, 1973).

Fig. 5-18A. Near the eruptive vent at Alae (upper left) most lava is pahoehoe, not having yet undergone the transition to aa. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

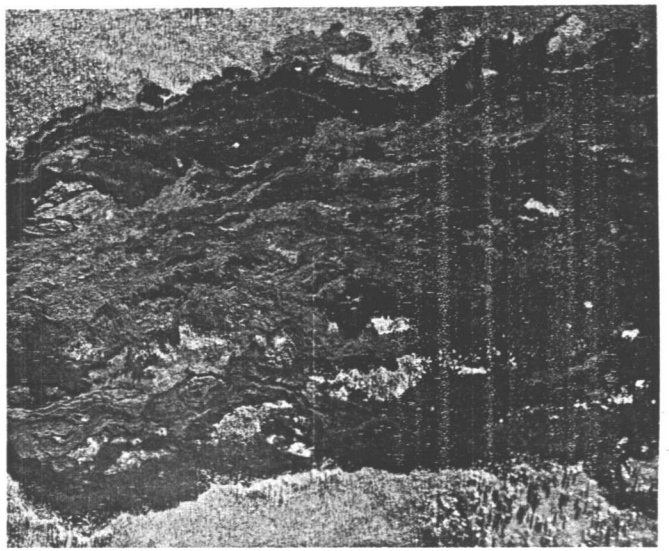


Fig. 5-18B. Lava about 4 km south of vent at Alae. Lava flows, originally pahoehoe, have gradually changed to aa as their viscosity increased. Here, new pahoehoe has emerged from lava tubes and encroached upon the earlier aa. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

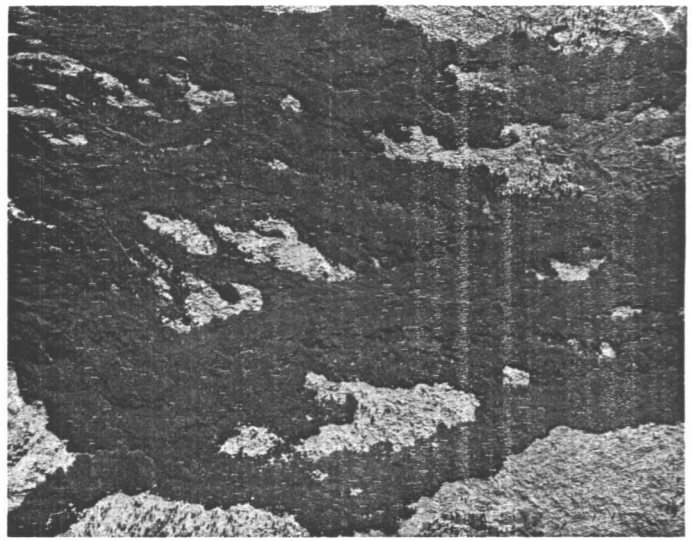


Fig. 5-18C. Lava about 6 km south of vent at Alae. Most of the lava is aa. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

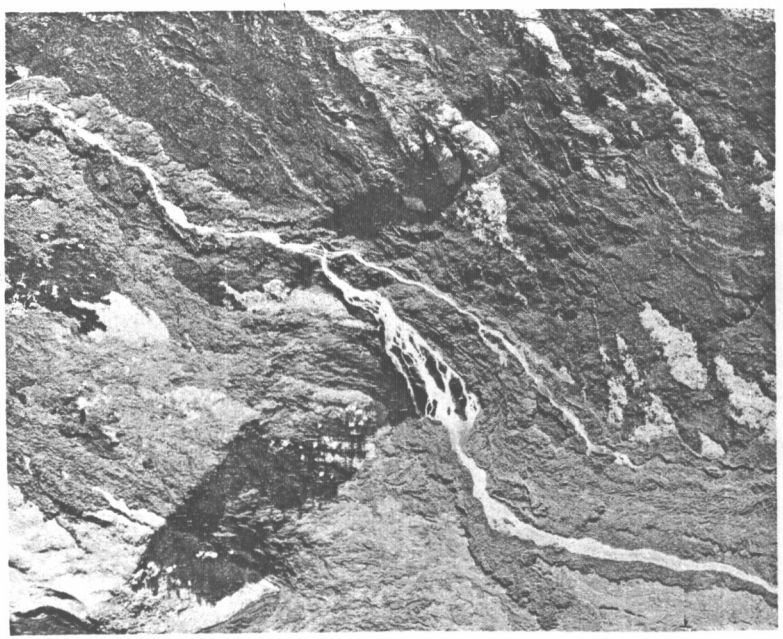


Fig. 5-19. Braiding of lava stream on a steep slope. This active lava stream, flowing southward over poliokeawe Pali, a 165-m-high fault scarp, divided into a braided pattern on the steep slope. On the relatively gentle slopes above and below the scarp the stream was flowing within fewer channels. The stream was flowing over earlier aa from the same eruptive episode. Above the scarp the active lava was pahoehoe, but it changed to aa as it descended the scarp. Below the scarp the active lava was entirely aa. (*Photo: R. M. Towill Corporation, June 1, 1974.*)

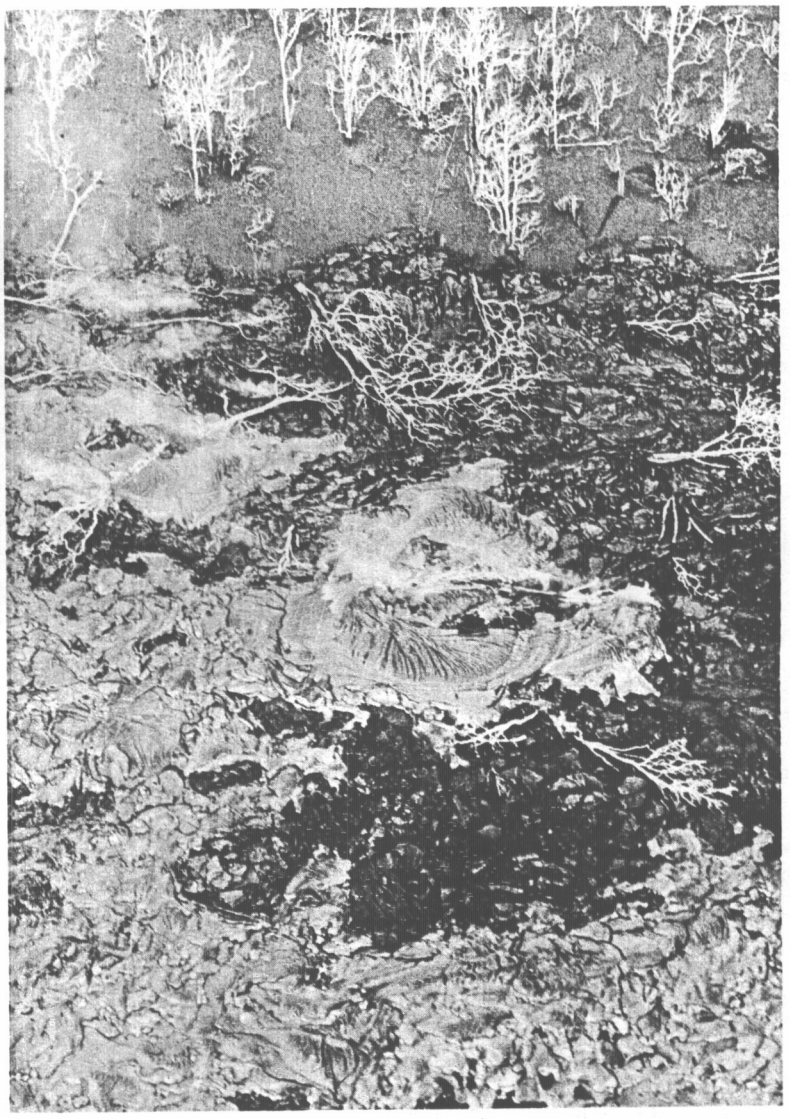


Fig. 5-20. Pahoehoe veneering lava transitional between pahoehoe and aa. New pahoehoe is actively encroaching on rough pahoehoe produced earlier by the same eruptive episode. The trees had been killed and partly buried by pumice erupted during an episode of high fountaining from Mauna Ulu in 1969. These trees are now being burned by the advancing pahoehoe. (*Photo: J. P. Lockwood, U.S.G.S., March 27, 1974.*)

Fig. 5-21. Development of lava tubes (see Greeley, 1971, 1972; Cruikshank and Wood, 1972; Peterson and Swanson, 1974).

Fig. 5-21A. Downstream growth of a lava tube roof. A crust is developing over a lava stream about 8 m wide, flowing from right to left. Lava accretes to small, flexible fingers on the downstream edge of the crust, and the growing crust gradually roofs over the entire stream, creating a lava tube. (*Photo: D. W. Peterson, U.S.G.S., February 1971.*)

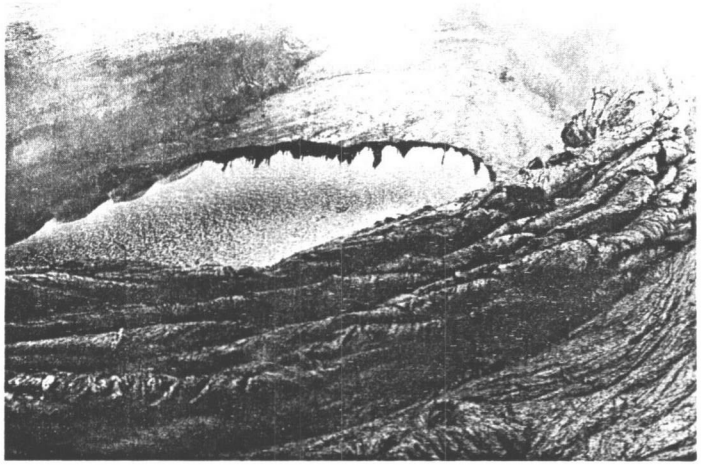


Fig. 5-21B. Sudden drop in level of a lava stream resulted in partial collapse of a thin roof that had been solidifying on the stream surface. Slender lava stalactites dangle from the roof. Such a roof may ultimately collapse completely, or, if the stream rises to a suitable level may continue to grow and achieve greater strength. Stream was about 3 m wide. (*Photo: D. W. Peterson, U.S.G.S., December 1972.*)

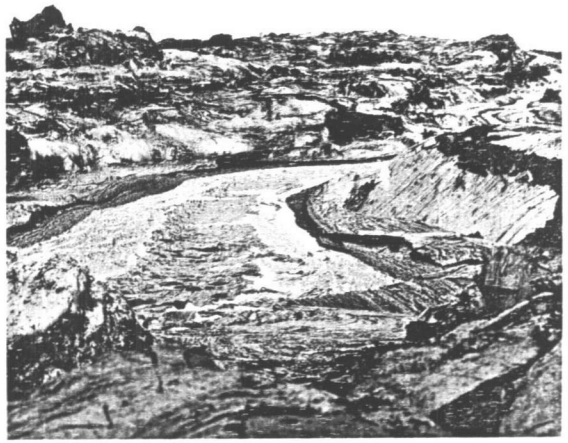


Fig. 5-21C. Growth of the roof of a lava tube roof by accretion to the channel banks; stream about 5 m wide. Stream flow is toward observer. A thin crust is growing along the channel margins, and may eventually completely roof over the channel. Wrinkled skin of partly solidified lava floats on the stream; where such skin encounters obstructions, it aids in roof development (see fig. 5-21D). (*Photo: R. T. Holcomb, U.S.G.S., October 29, 1972.*)

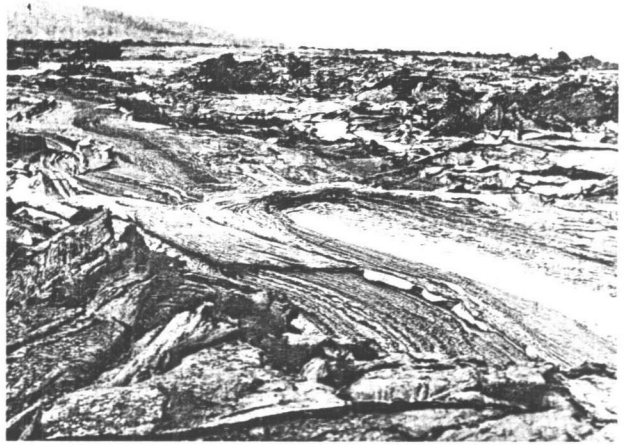


Fig. 5-21D. Growth of the roof of a lava tube by accretion to the upstream edge of the roof. View is downstream from the same point as Figure 21C; stream flow is right to left. The wrinkled plates of crust floating on the stream are piling up against the upstream edge of the crust that has already formed a roof across the stream. Distance from right edge of photo to roof is about 5 m. (*Photo: R. T. Holcomb, U.S.G.S., October 29, 1972.*)

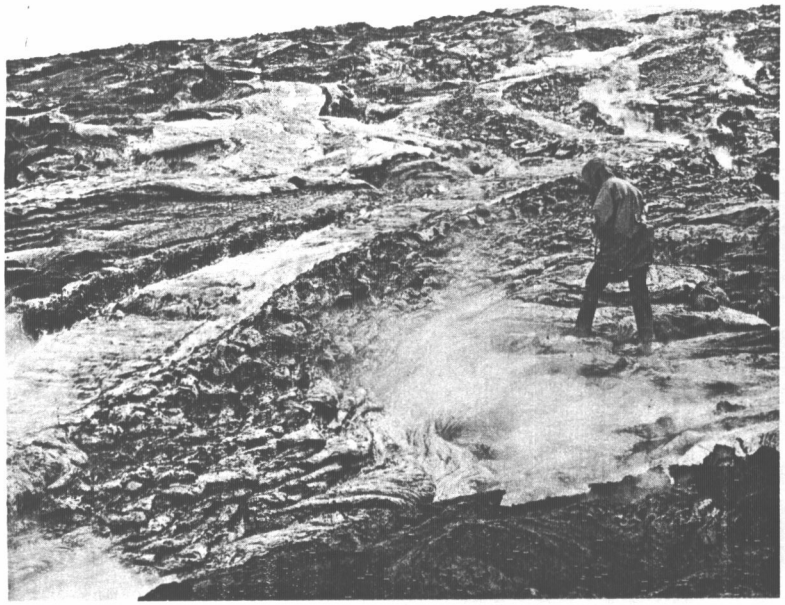


Fig. 5-22. Development of lava tubes by accretion to lava levees. Lava accretes to the margins of a perched lava stream, confined by steep-sided levees about 1 m high, and brief surges add new material to the levee top. As the levees grow upward, they also tend to grow inward, narrowing the surface width of the stream. A continuation of the process may completely enclose the stream. (*Photo: R. T. Holcomb, U.S.G.S., March 5, 1974.*)

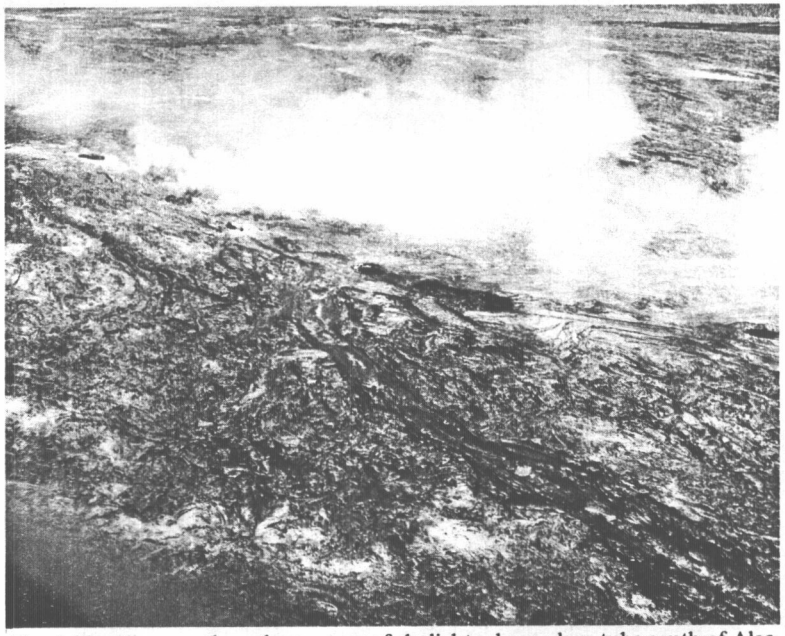


Fig. 5-23. View northward up a row of skylights along a lava tube south of Alae. The main vent of Alae is in the upper center. Overflows from the skylights have fed fresh dark flows extending across the foreground. Nearest skylight is about 10 by 30 m. (*Photo: R. T. Holcomb, U.S.G.S., December 9, 1973.*)

Fig. 5-24. Views through skylights into active lava tubes.

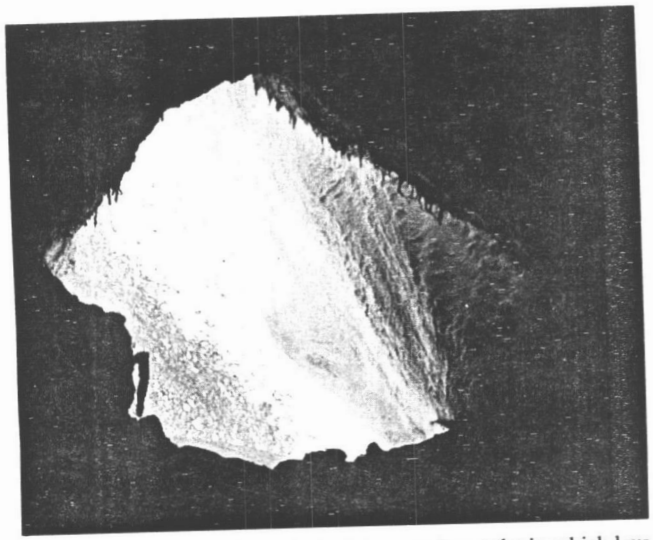


Fig. 5-24A. Downward view through skylight into lava tube in which lava, about 4 m below the surface, is flowing from lower right toward upper left. Terraced ridges mark the incandescent walls of the lava tube and indicate former levels of flow. Small stalactites hang from the roof of the tube. (*Photo: D. W. Peterson, U.S.G.S., September 7, 1972.*)

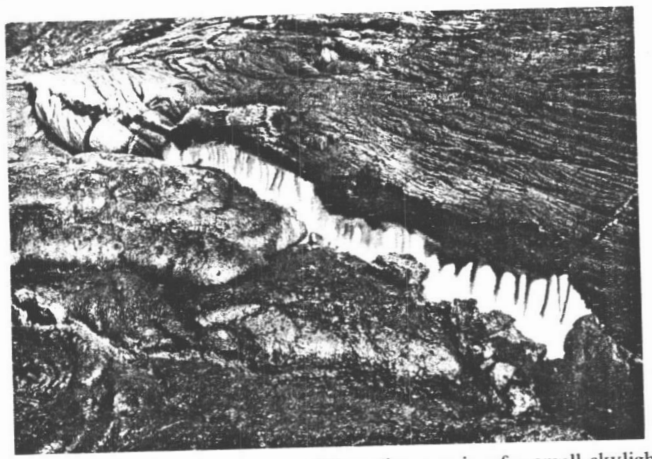
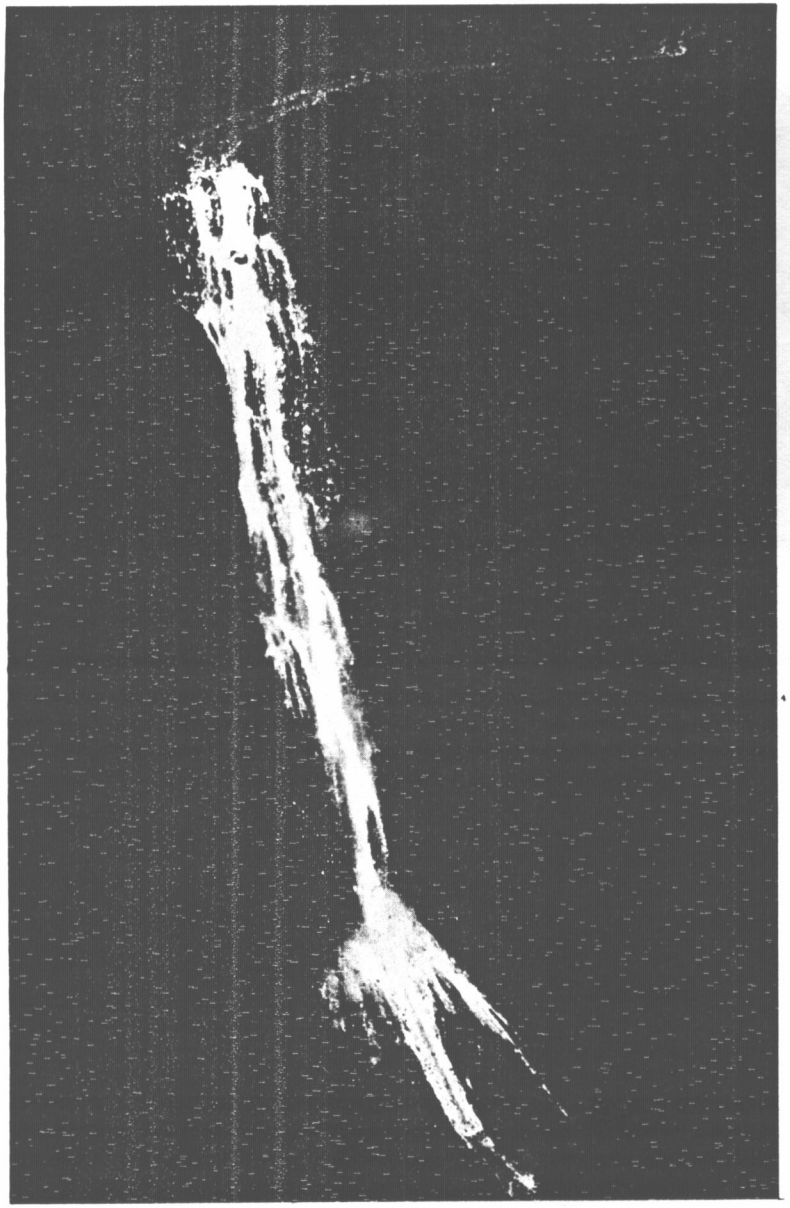


Fig. 5-24B. Well developed stalactites fringe the margin of a small skylight over an active lava tube. Serrated "teeth," uniformly on the left side of the stalactites, may be sculptured by gas streaming out of the skylight. Width of opening is about 20 cm. (*Photo: D. W. Peterson, U.S.G.S., August 23, 1970.*)

Fig. 5-24C. With time the roof of a lava tube becomes thicker and stronger, both by slow accretion and by addition of surface flows. The stream surface here is about 3 m below the ground surface; some streams are as much as 20 m below the surface. Such levels suggest erosion of channel bottoms. (*Photo: R. T. Holcomb, U.S.G.S., February 6, 1973.*)

Fig. 5-24D. One way to determine if lava streams erode their beds is to plumb the depth of the streams at intervals. Such opportunities are rare. (*Photo: R. I. Tilling, U.S.G.S., January 30, 1973.*)

Fig. 5-25. A talus cone of aa clinkers.



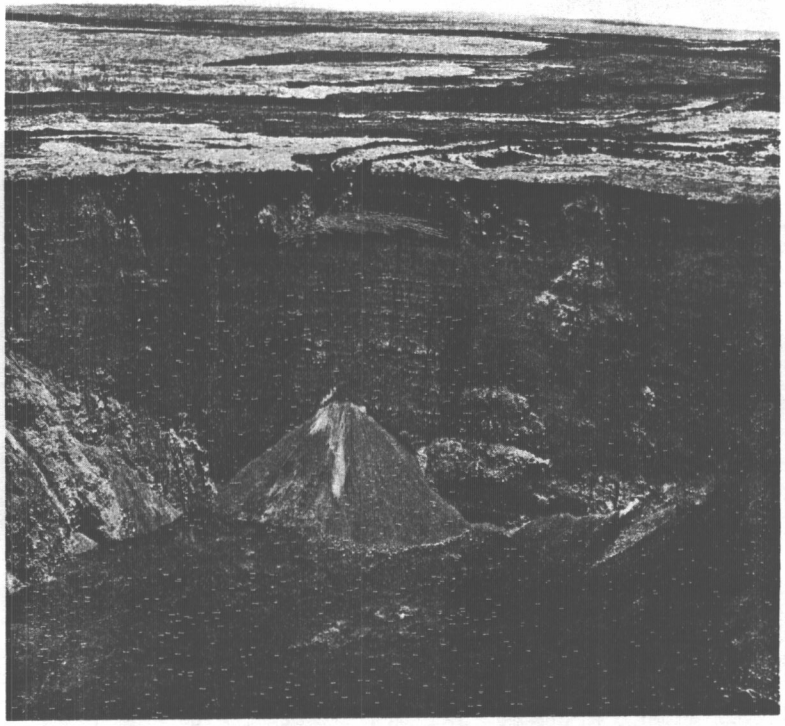


Fig. 5-25B. Nearly the same view, in daylight, showing the talus cone produced by inflow such as seen in figure 25A. This lava barely veneered the crater walls, and little flowed beyond the base of the talus cone. (*Photo: D. W. Peterson, U.S.G.S., April 23, 1972.*)

Fig, 5-25A. A night-time aerial view showing a single stream of lava cascading over the western edge of Makaopuhi Crater, falling 150 m down the wall, and accumulating as a cone of aa clinkers at the base of the cliff. (*Photo: D. W. Peterson, U.S.G.S., March 19, 1972.*)

Fig. 5-26. Subsequent development of talus-and-lava cones at Makaopuhi.

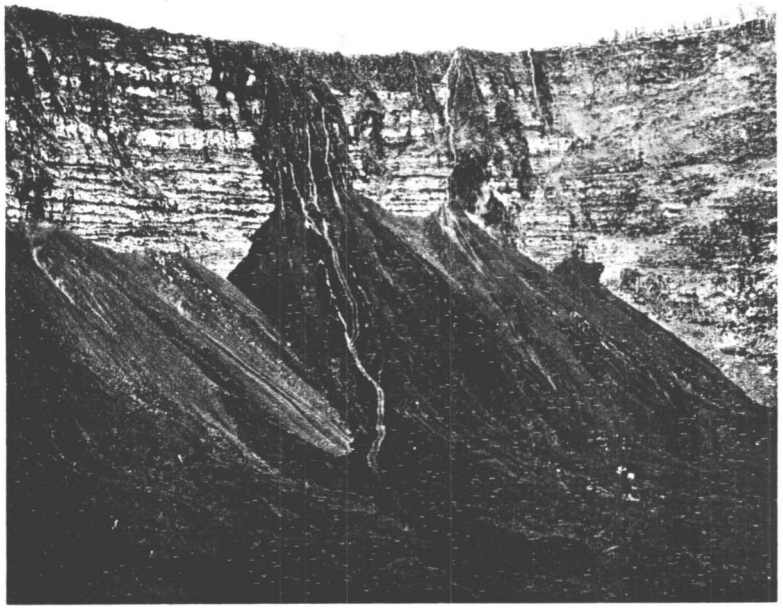


Fig. 5-26A. Some of the larger streams formed lava tubes that extend continuously from the crater rim to the apex of the large talus-and-lava cones; these tubes feed aa flows that reach the base of the cone and spread across the floor of the crater. Some tubes, however, extend below the surface of the cones and conduct lava underground all the way to the crater floor. The cones on the left are entirely of fragmental talus, produced by small streams unable to mainatin coherence as they descend the walls. (*Photo: W. A. Duffield, U.S.G.S., June 30, 1972.*)

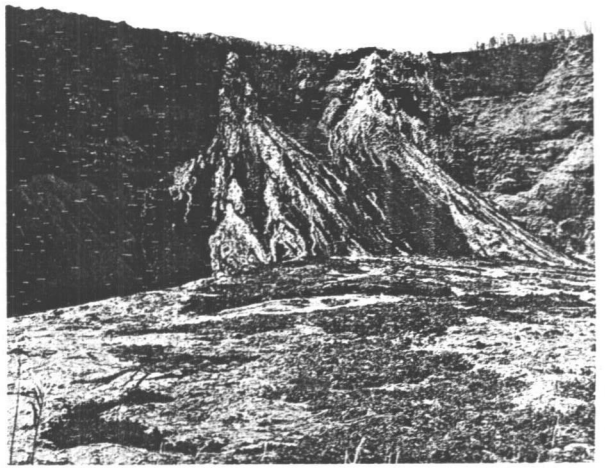


Fig. 5-26B. Same view as figure 27A, showing the talus-and-lava cones in a more advanced stage of development. Carapaces on the crater walls completely hide the lava streams, which continue to flow in lava tubes from the rim of the crater, down the walls, through the cones, and on to the floor of the crater. Much of the lava does not emerge on the surface of the floor, but instead is fed into a reservoir beneath the crust, doming the crust in the process. (*Photo: R. T. Holcomb, U.S.G.S., August 2, 1972.*)

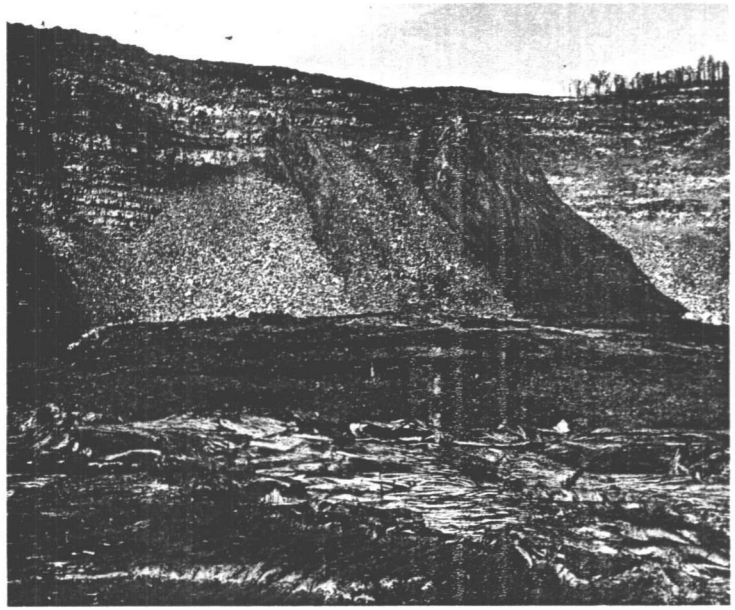


Fig. 5-26C. The lava carapaces on the crater walls are unstable, and when flow declined the carapaces collapsed. The cone surfaces are here littered with a veneer of talus from the collapsed carapaces. Men working on the crater floor indicate scale. (*Photo: R. T. Holcomb, U.S.G.S., October 29, 1972.*)

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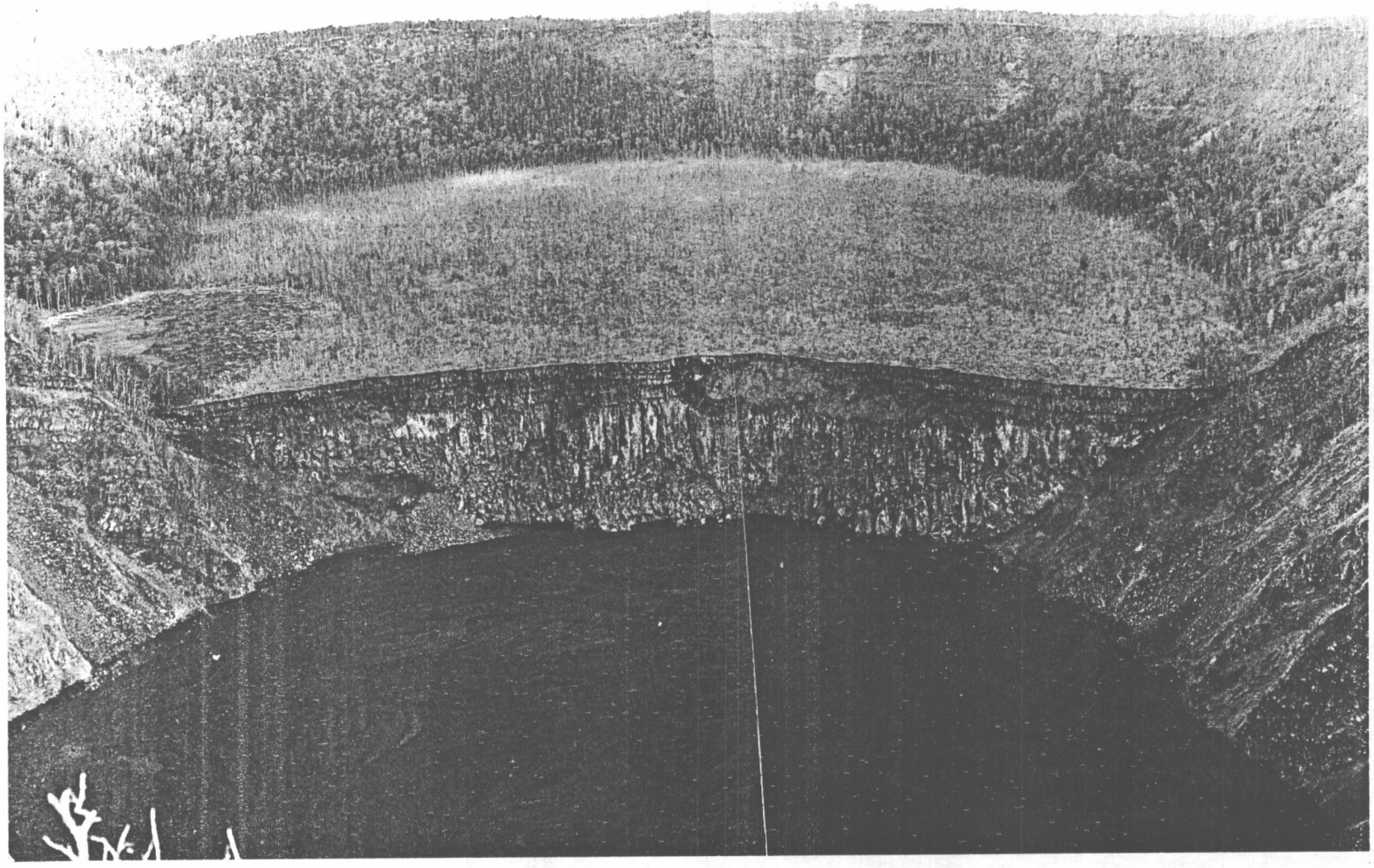

Fig. 5-27. View east across Makaopuhi Crater before the inflow of 1972 and 1973. The eastern part of the crater is partly filled by a prehistoric lava lake subsequently covered by several thin flows; the western pit (foreground) later collapsed to expose the interior of the lake (Moore and Evans, 1967). A small lava pad on the left hand side of the mezzanine was produced during the eruption of 1965, which also deposited some 83 m of lava in the western pit (Wright and others, 1968). The 1965 lava lake was covered by aa that flowed over the west rim of the crater in 1969 and 1971, but above this aa, the high lava mark left in 1965 can still be seen. (*Photo: D. W. Peterson, U.S.G.S., March 21, 1972.*)

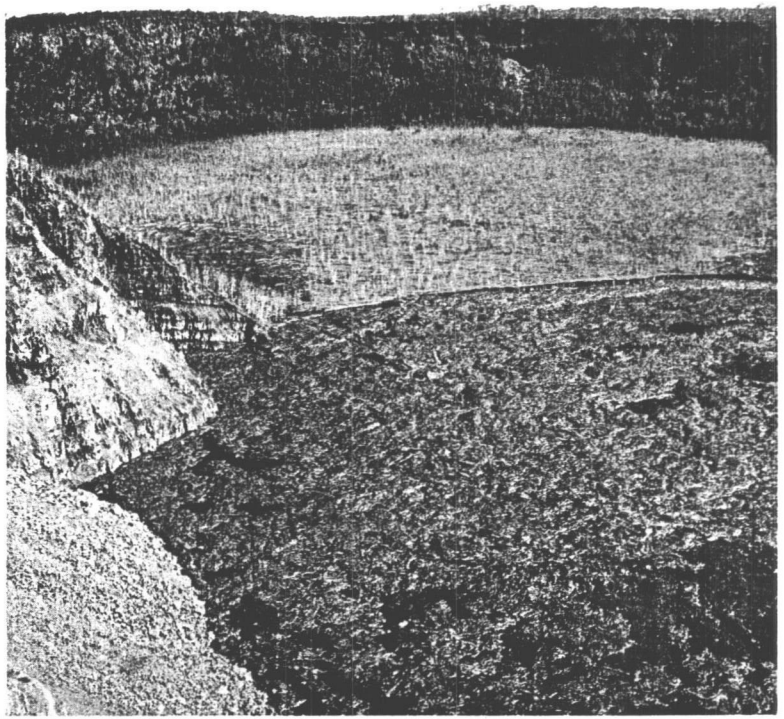

Fig. 5-28. Makaopuhi Crater in early 1973, after the west pit had nearly filled with lava. The dark areas at lower right are aa flows of June 1972; these remnants had served as reference markers on the surface of the crust during its upward doming of tens of meters by the subsurface inflow. (*Photo: D. W. Peterson, U.S.G.S., January 26, 1973.*)

Fig. 5-29. Deformation at the western margin of the rising crater floor in Makaopuhi Crater.

Fig. 5-29A. Tensional cracks and a moat at the base of the talus-and-lava cone have formed as the lake crust on floor of the pit rises. Molten lava below the crust is being fed by tubes extending through the talus-and-lava cones. (The pipe at the left edge of the photo is a remnant of the railing at the former overlook on the southwest rim of the crater.) (*Photo: R. T. Holcomb, U.S.G.S., August 4, 1972.*)

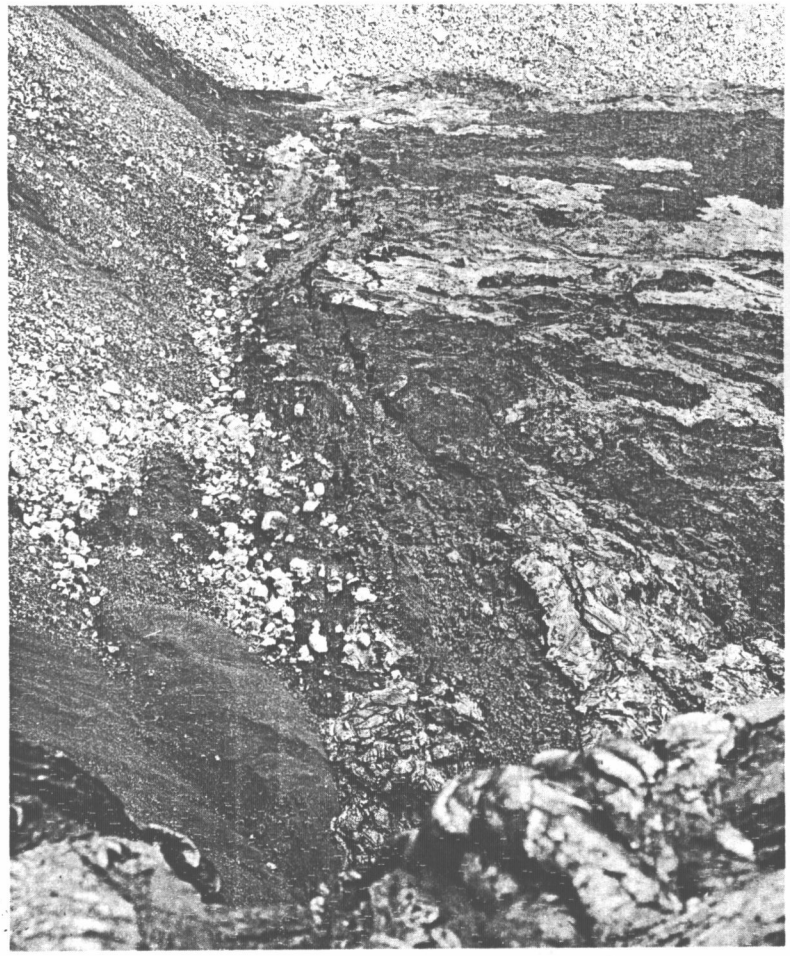

Fig. 5-29B. The lake surface has continued to rise, deepening the moat at the base of the talus-and-lava cones and widening the tensional cracks. A fault cuts the fine talus cone, lower left, and the base of the cone is being uplifted. Rockfalls from above are supplying large fragments to the moat. (*Photo: R. T. Holcomb, U.S.G.S., August 16, 1972.*)

Fig. 5-30. Deformation at the east edge of the rising crater floor, Makaopuhi Crater. In this view the nearly flooded mezzanine cliff is only about 2 m high and decreases as the crater floor rises like a piston. The rise is accompanied by tilting of marginal blocks of the crust and oozing of viscous lava into the tensional cracks around the margin. (*Photo: R. T. Holcomb, U.S.G.S., January 12, 1973.*)

Fig. 5-31. Ultimate engulfment of the mezzanine cliff in Makaopuhi Crater.

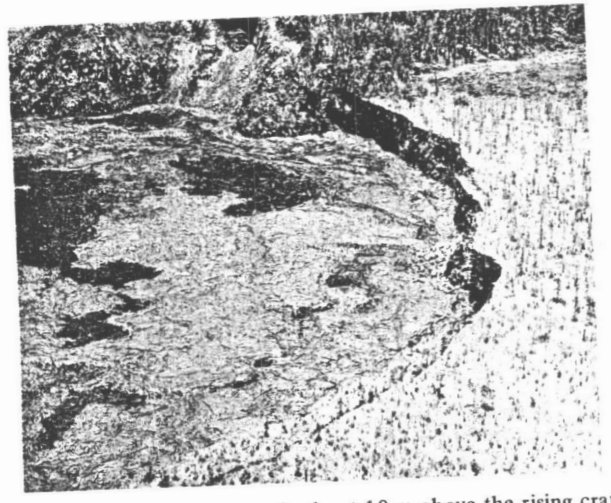

Fig. 5-31A. Mezzanine in this view is about 10 m above the rising crater floor. (*Photo: R. T. Holcomb, U.S.G.S., August 4, 1972.*)

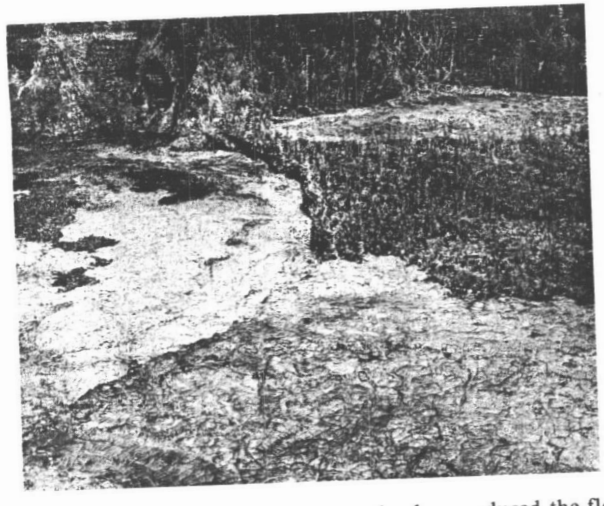

Fig. 5-31B. An outbreak of lava on the mezzanine has produced the flow in the foreground. (The flow in the background was erupted in 1965.) This outbreak was probably induced by artesian-like pressure in the confined reservoir in the western pit forcing open cracks underlying the mezzanine. (*Photo: R. T. Holcomb, U.S.G.S., August 16, 1972.*)

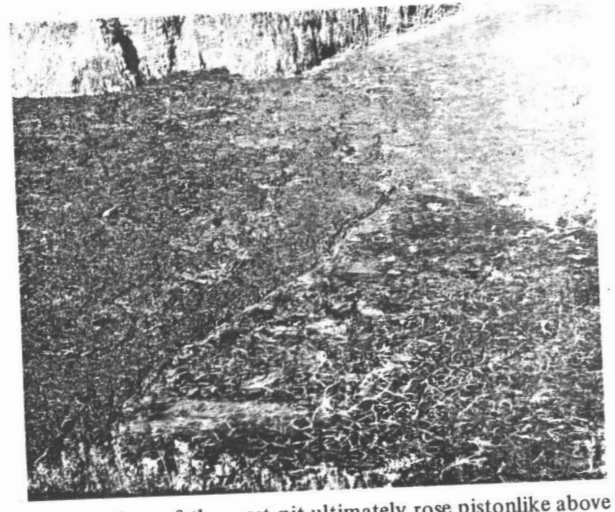

Fig. 5-31C. The surface of the west pit ultimately rose pistonlike above the level of the mezzanine; in this view a small scarp faces the mezzanine. Subsequently, molten lava broke through the rising surface and spread eastward across the mezzanine. (*Photo: R. T. Holcomb, U.S.G.S., February 22, 1973.*)

Fig. 5-32. Aerial views of tube-fed pahoehoe entering the ocean.

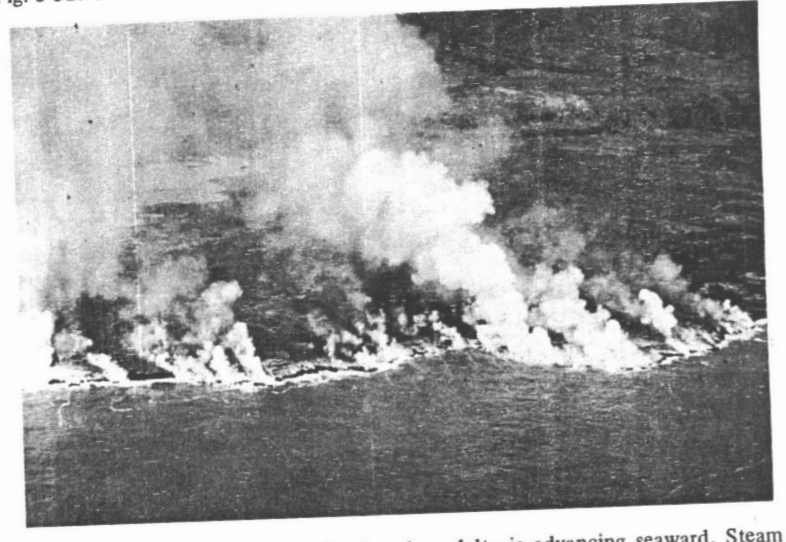

Fig. 5-32A. The front of a pahoehoe lava delta is advancing seaward. Steam clouds rise from hot rocks being splashed by waves. (*Photo: D. A. Swanson, U.S.G.S., March 21, 1972.*)

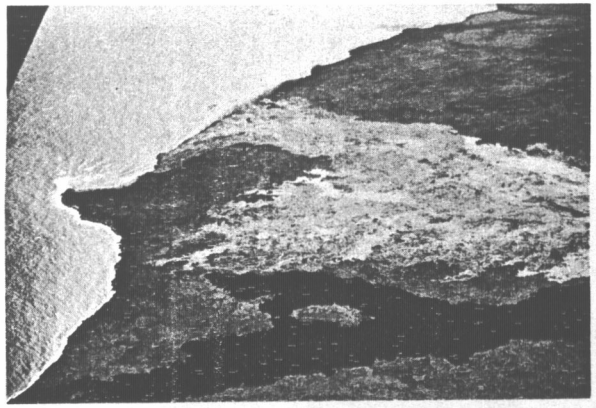

Fig. 5-32B. Fresh pahoehoe extends across the coastal flats and enters the ocean west of Apua Point; a steam cloud rises where lava meets the water. The prominent dark flow in the foreground is a 1969 aa flow from Mauna Ulu. (*Photo: D. W. Peterson, U.S.G.S., March 22, 1973.*)

Fig. 5-33. Variations in activity as lava enters the water.

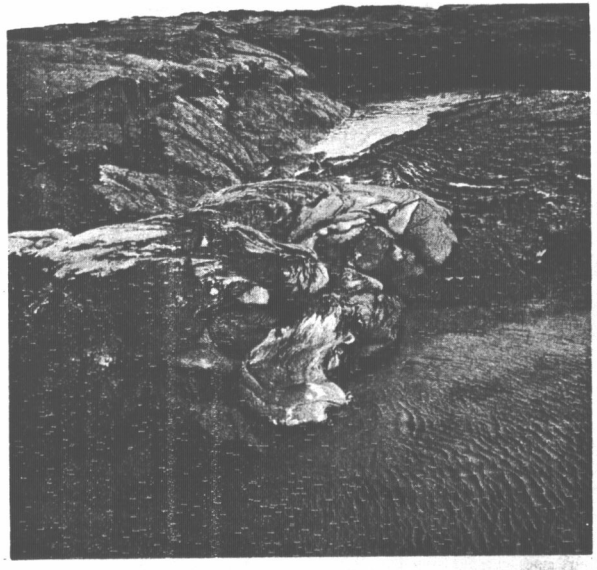

Fig. 5-33A. A lava toe quietly enters a tidal pool; no steaming is produced because of low thermal conductivity of chilled crust and large volume of water relative to the amount of lava. (*Photo: R. L. Christiansen, U.S.G.S., August 24, 1972.*)

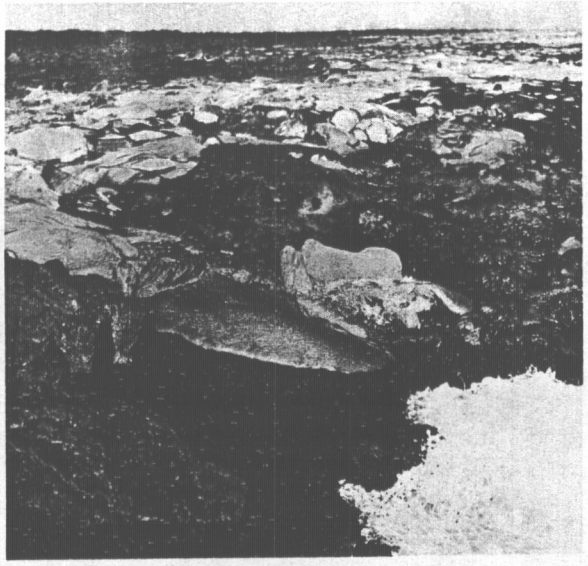

Fig. 5-33B. A tongue of pahoehoe extends across a black sand beach as surf rushes toward it. White salt encrusts some surfaces where thin films of sea water have repeatedly boiled from the hot rock. (*Photo: D. W. Peterson, U.S.G.S., August 24, 1972.*)

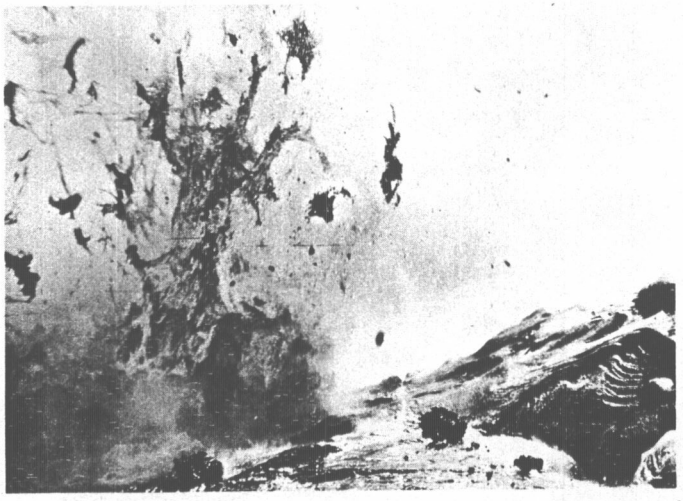

Fig. 5-33C. A strong explosion at the entrance to a littoral lava tube, produced when surf flooded the tube opening, abruptly expanding to steam in the confined space. Height of photo is about 4 m. (*Photo: D. W. Peterson, U.S.G.S., April 12, 1972.*)

Fig. 5-34. Chilling of a pahoehoe toe by the surf. (*Photos: D. A. Swanson, U.S.G.S., April 19, 1971.*)

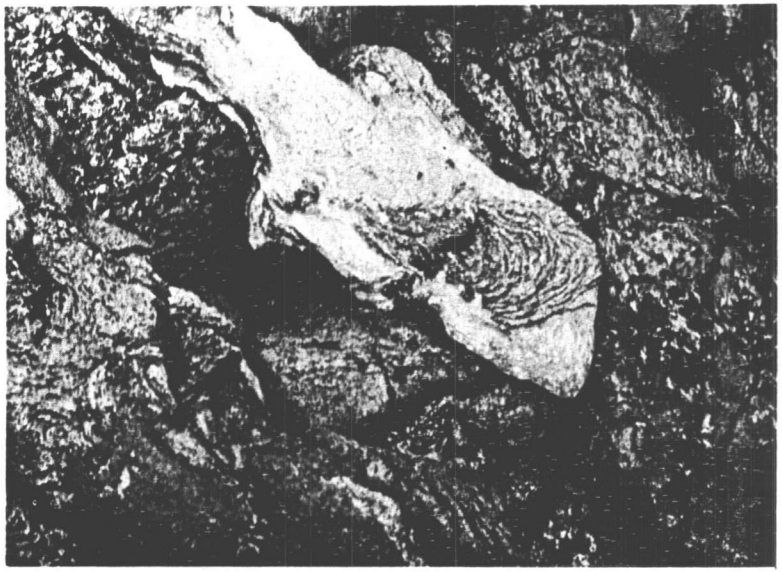

Fig. 5-34A. A tongue of pahoehoe oozes down the front of a lava delta; length of toe is about 1 m.

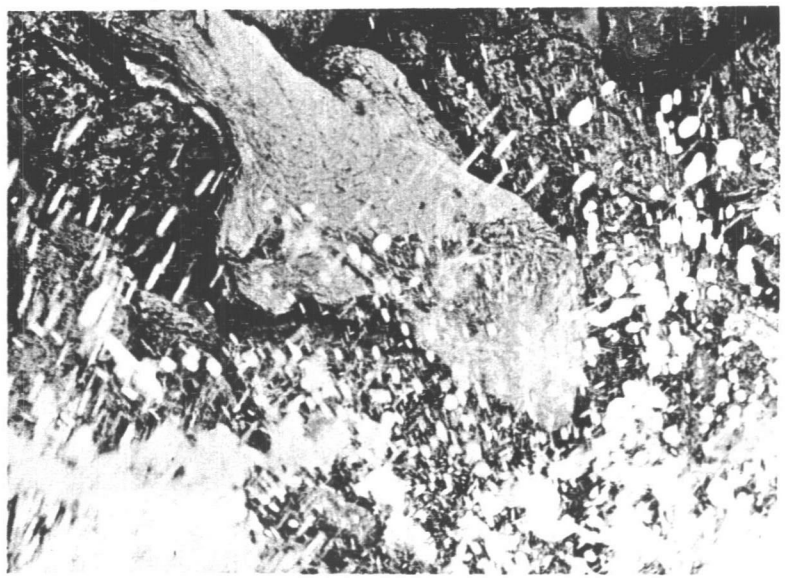

Fig. 5-34B. Surf splashes onto the surface of the lava toe; an instant later the toe was engulfed by the wave.

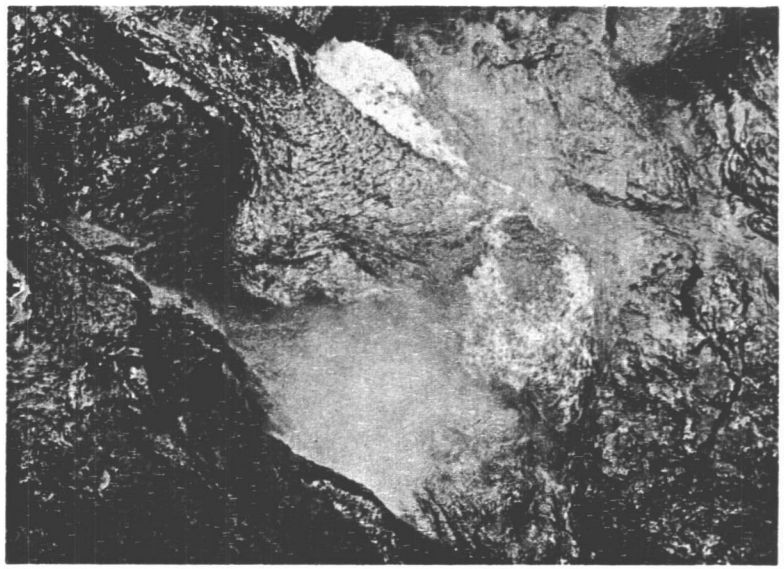

Fig. 5-34C. The wave quenched the toe, forming a solid skin and stopping the toe's advance. Water boils from the surface of the toe. Lava will soon break through the skin, and a new toe will flow until stopped by another wave.

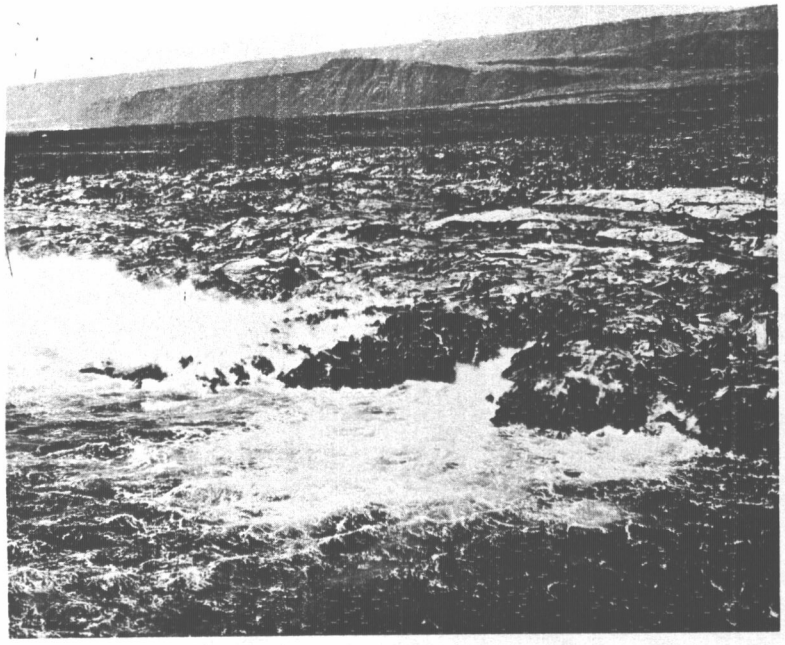

Fig. 5-35. The front of an active lava delta may assume an irregular and lobate form. Each lobe is fed by branches of a lava tube system. Steam rises where water splashes on active lava or hot rocks. (*Photo: D. W. Peterson, U.S.G.S., March 4, 1973.*)

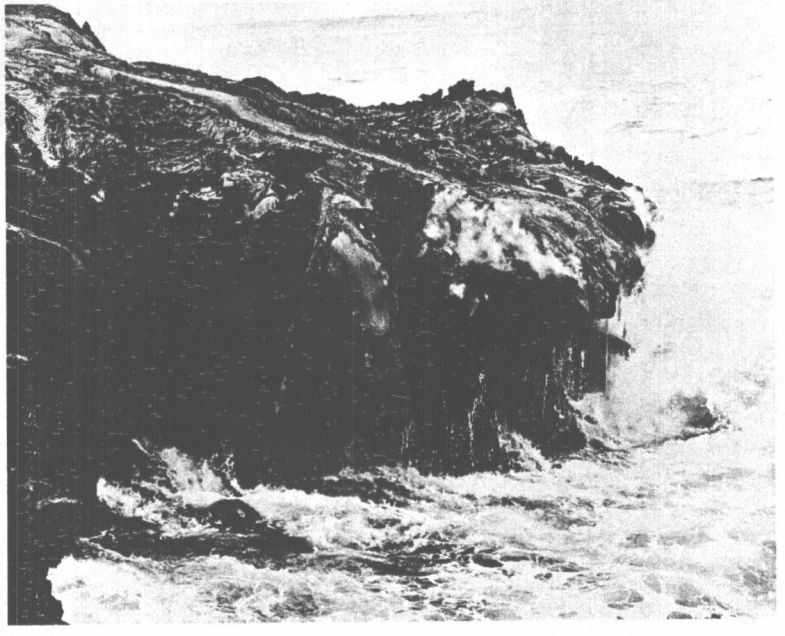

Fig. 5-36. A close-up of lava encountering the sea. An active toe enters the water in the center. As lava advances seaward, waves tend to undercut the face, and new lava extends the overhanging lip. In this view a wave has just receded and small driblets of lava emerge from the overhang on the right and drop vertically into the water. (*Photo: D. W. Peterson, U.S.G.S., April 4, 1973.*)

Fig. 5-37. Erosion of the front of the lava delta.

Fig. 5-37A. When inflow ceases, erosional processes immediately become dominant. The front of the delta is straightened, and a low sea cliff is quickly cut along the shore. Coarse, angular debris commonly accumulates at the base of the cliff. (*Photo: D. W. Peterson, U.S.G.S., April 26, 1973.*)

Fig. 5-37B. Kealakomo lava delta almost a year after cessation of activity. Erosion of the lava front has continued, the front of the delta has been further straightened, and boulders and cobbles broken from the lava are being rapidly rounded. (*Photo: D. W. Peterson, U.S.G.S., February 23, 1972.*)

Fig. 5-37C. The finer-sized material eroded from the lava delta is sorted and deposited in relatively quiet inlets along the margins of the lava delta, forming new black sand beaches. (*Photo: D. W. Peterson, U.S.G.S., September 1972.*)

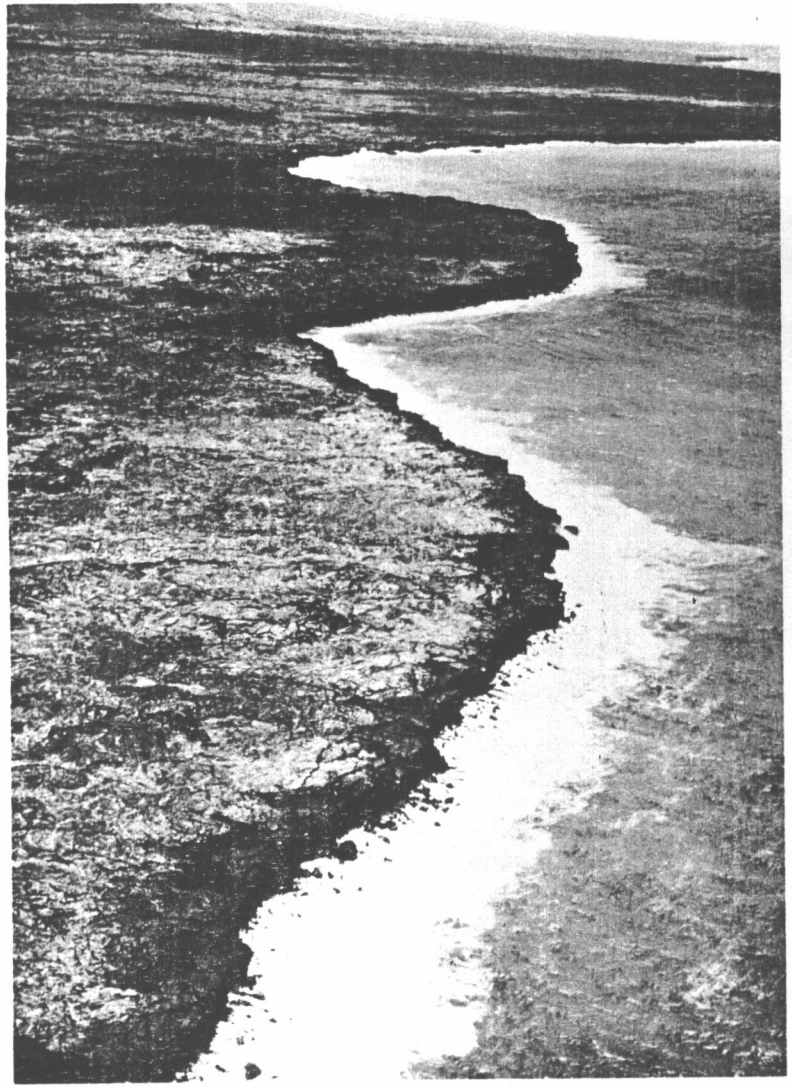

Fig. 5-37D. Aerial view eastward along the front of the Kealakomo lava delta, showing the progress of erosion just a few weeks after lava inflow ceased on this segment of the lava delta. Small lobes on the front of the delta, such as are seen in figure 5-37A, have been destroyed, and the straightened coastline shows only broad points extending seaward. The wave-cut sea cliff is from 2 to 5 m in height. (*Photo: D. W. Peterson, U.S.G.S., June 25, 1971.*)

Fig. 5-38. Coastline changes caused by lava entering the sea.

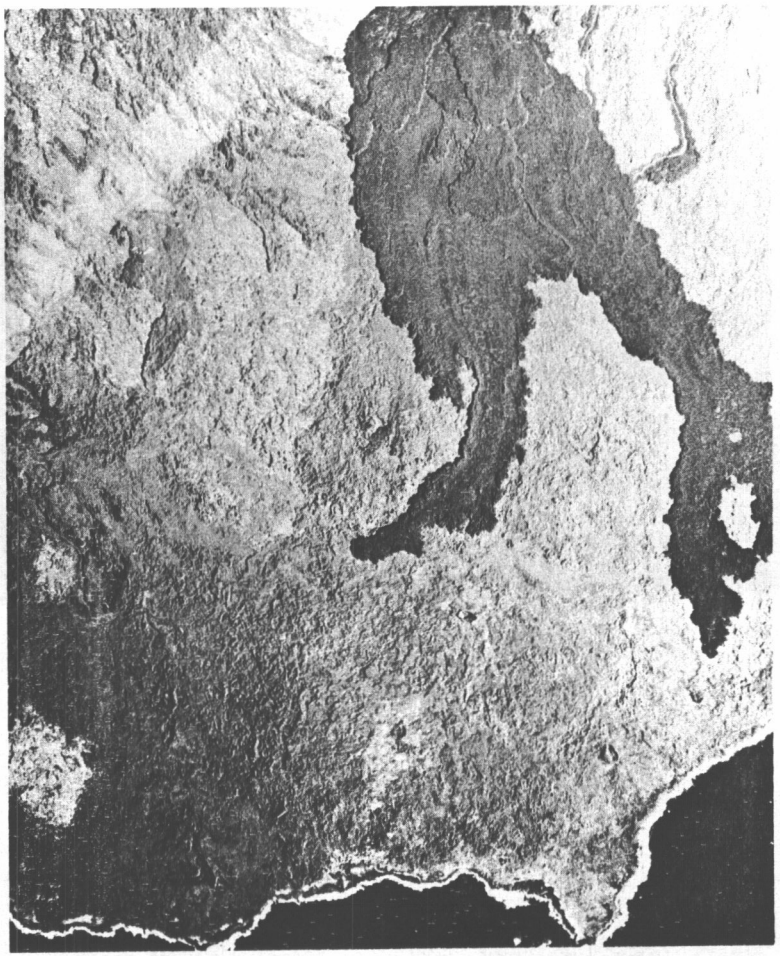

Fig. 5-38A. View of Apua Point area before pahoehoe flows covered the region in 1973. The prominent dark flows are aa erupted from Mauna Ulu in 1969. (*Photo: R. M. Towill Corporation, October 19, 1972.*)

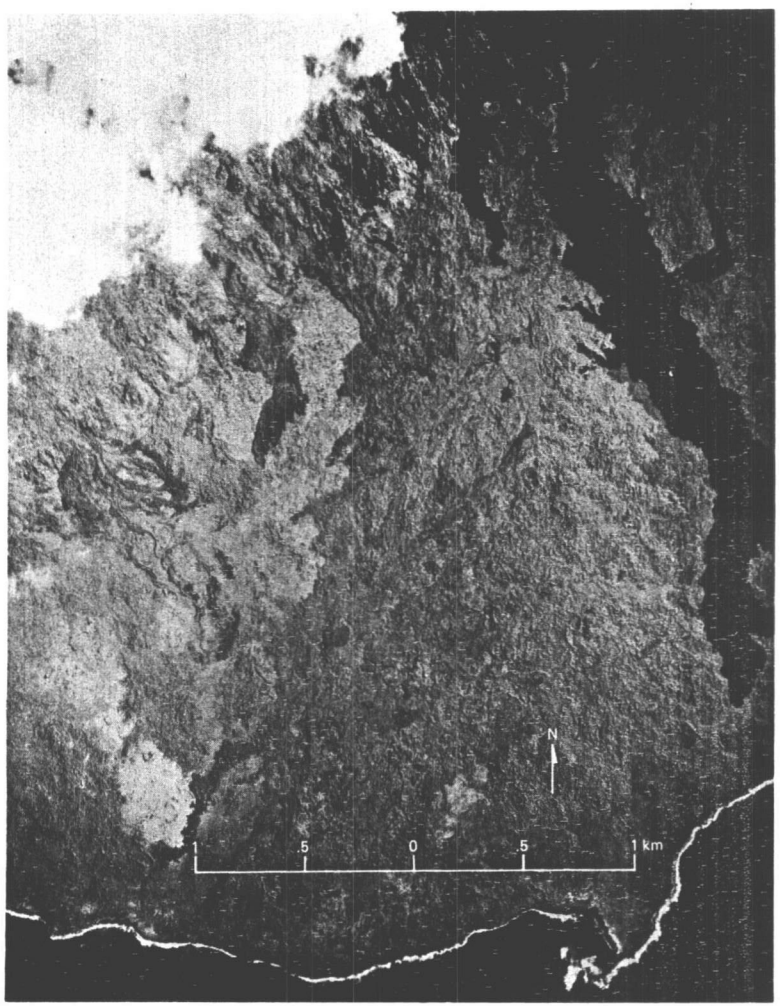

Fig. 5-38B. The same view after pahoehoe flows covered the area in early 1973. Much of the 1969 aa has been buried by the new pahoehoe, and a new lava delta west of Apua Point has modified the shape of the coastline. (*Photo: R. M. Towill Corporation, June 1, 1974.*)

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6. GEOLOGY OF THE ISLAND OF HAWAII

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THE GEOLOGIC HISTORY OF THE HAWAIIAN ARCHIPELAGO is probably a good deal more complex than that revealed by the parts of the islands exposed to view above sea level. Far more exploration of the submerged portions, by both submarine geological studies and deep drilling, are needed before we will even begin to have the complete story. Only by lucky chance, during a demonstration cruise of a vessel of the Scripps Institution of Oceanography for members of the Pacific Science Congress, in 1961, were fragments of very ancient limestone dredged from off southern Oahu which showed for the first time that a coral reef had existed in that area before the present island was built. And since coral reef can grow only in shallow water, a still older volcanic ridge must have been present. It may have been a southeastward continuation of the ridge that underlies the Leeward Islands, but this is only conjecture, and its actual extent remains to be determined. Did it, and the reefs that crowned it, sink as a result of the subsidence of the Darwin Rise, that carried downward the guyots of the Mid-Pacific Mountains to the west of Hawaii? How much of the submarine portions of the Hawaiian mountains consists of pillow lavas, how much of hyaloclastite, how much of tephra formed by explosions where rising lava encountered sea water? Are the heavy masses that underlie Kailua on Oahu, and other caldera areas, accumulations of sunken olivine crystals, or are they portions of the earth's mantle that somehow have been shoved upward into the cores of the volcanoes? Only deep drill holes will supply the answers. The account of the geology of the individual Hawaiian islands on the following pages is only a progress report based very largely on the uppermost, visible parts of the Hawaiian volcanic range.

Even in their visible tops alone, the northwestern islands of the Hawaiian chain have had a considerably longer and more complex geological history than those to the southeast. They show more clearly the effects of outside events such as the changes of sea level during the glacial period, and their original forms have been far more extensively altered, so that the interpretation of their geology is more difficult. In this chapter the islands are described in turn, from southeast to northwest, in the order of increasing age and generally of increasing geological complexity.

Only the more salient features of their geology can be summarized here. For more details, both in facts and in the evidence for the interpretations presented, the reader should consult the original publications which are listed at the end of the chapter.

Hawaii

The island of Hawaii today consists of five volcanic mountains. All of them are very young, and three of the volcanoes have been active in historic time. At least two other volcanoes which helped to build the island have been buried by more recent ones. Kohala Mountain, which forms the northern end of the island (fig. 176), appears to be the oldest. Rocks exposed in the cliffs on its northeastern side have been shown by the potassium-argon method to be about 700,000 years old (table 18). The Kohala volcano had already reached nearly its final size before its southern flank was buried beneath lava flows from Mauna Kea, next to the south.

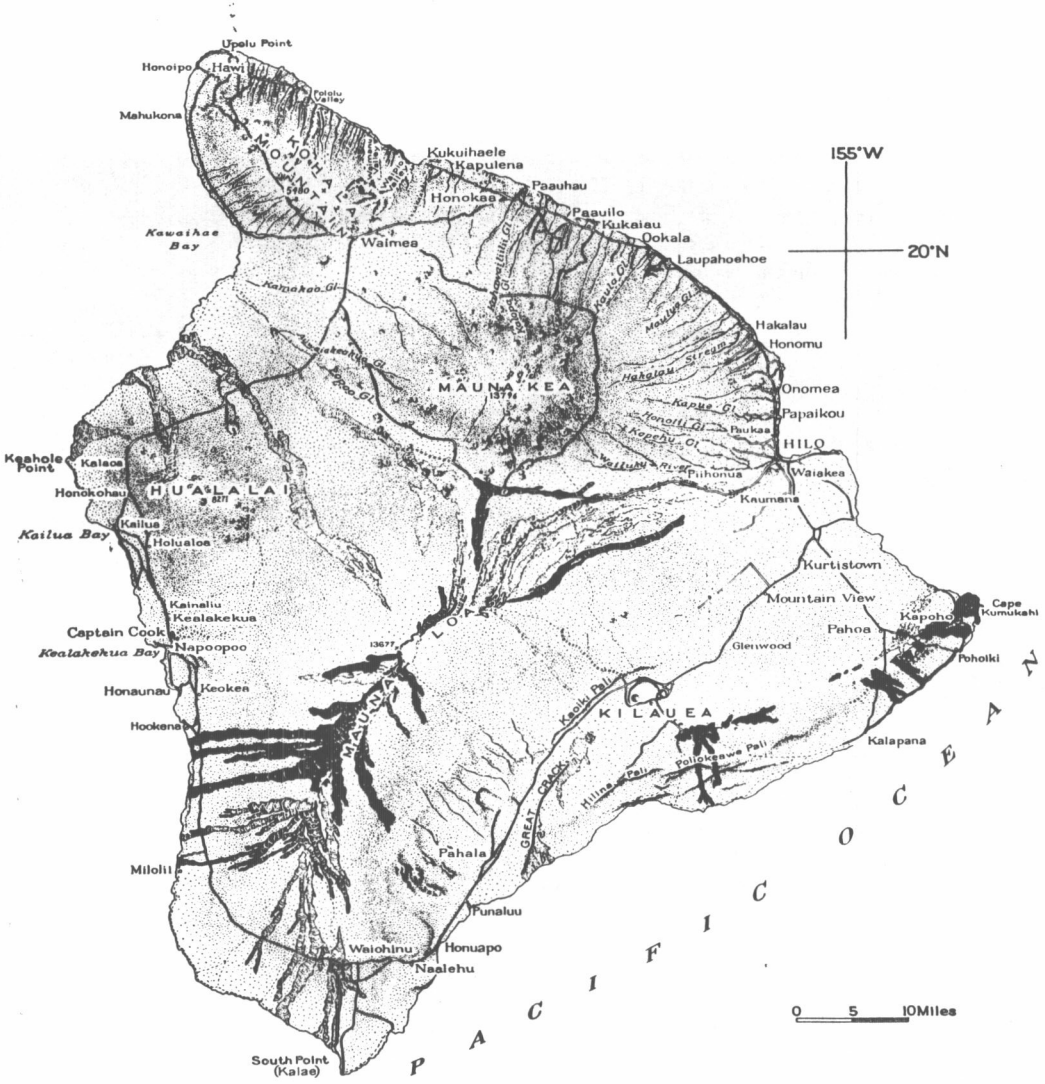


Figure 176. Topographic map of the island of Hawaii. (Modified after Stearns and Macdonald, 1946.)

About the same time as the birth of the Kohala volcano, or shortly afterward, another vent opened on the sea floor beneath the present south end of the island of Hawaii. Lavas from this southern vent built a shield volcano that rose to a height of about 8,000 feet above sea level in the region northwest of the present town of Naalehu. Potassium-argon determinations indicate that its rocks are about 100,000 to 500,000 years old. The rocks are known as the Ninole Volcanic Series after the now-abandoned village of Ninole, near which they are exposed. The Ninole volcano ceased activity perhaps as long ago as 100,000 years, and stream erosion cut deeply into the shield, forming a series of large valleys separated by flat-topped ridges. This old topography has been almost completely buried by the present Mauna Loa volcano, but the tops of some of the ridges can be seen projecting through the Mauna Loa lavas north of Naalehu, where they form the prominent hills called Kaiholena and Puu Enuhe, near Pahala (figs. 177 and 178).

The rocks of Mauna Kea overlap those of Kohala Mountain and must, therefore, be younger. The oldest of them that are now exposed above sea level are in the sea cliff at Laupahoehoe, on the Hamakua (northeastern) Coast (fig. 187). All of the visible portion of Mauna Kea must be more recent than middle Pleistocene. Nevertheless, Mauna Kea had already reached its present size by the time the last Pleistocene glacier disappeared from its summit, 15,000 or so years ago (see chap. 14). Only three lava flows are known that are later than the glacial moraines. There are no Hawaiian traditions of eruptions of Mauna Kea, and it probably has not been active during the last 2,000 years, but it is quite impossible to say whether the volcano is extinct or only dormant. Occasional earthquakes originate beneath it and emphasize the possibility that it may someday erupt again.

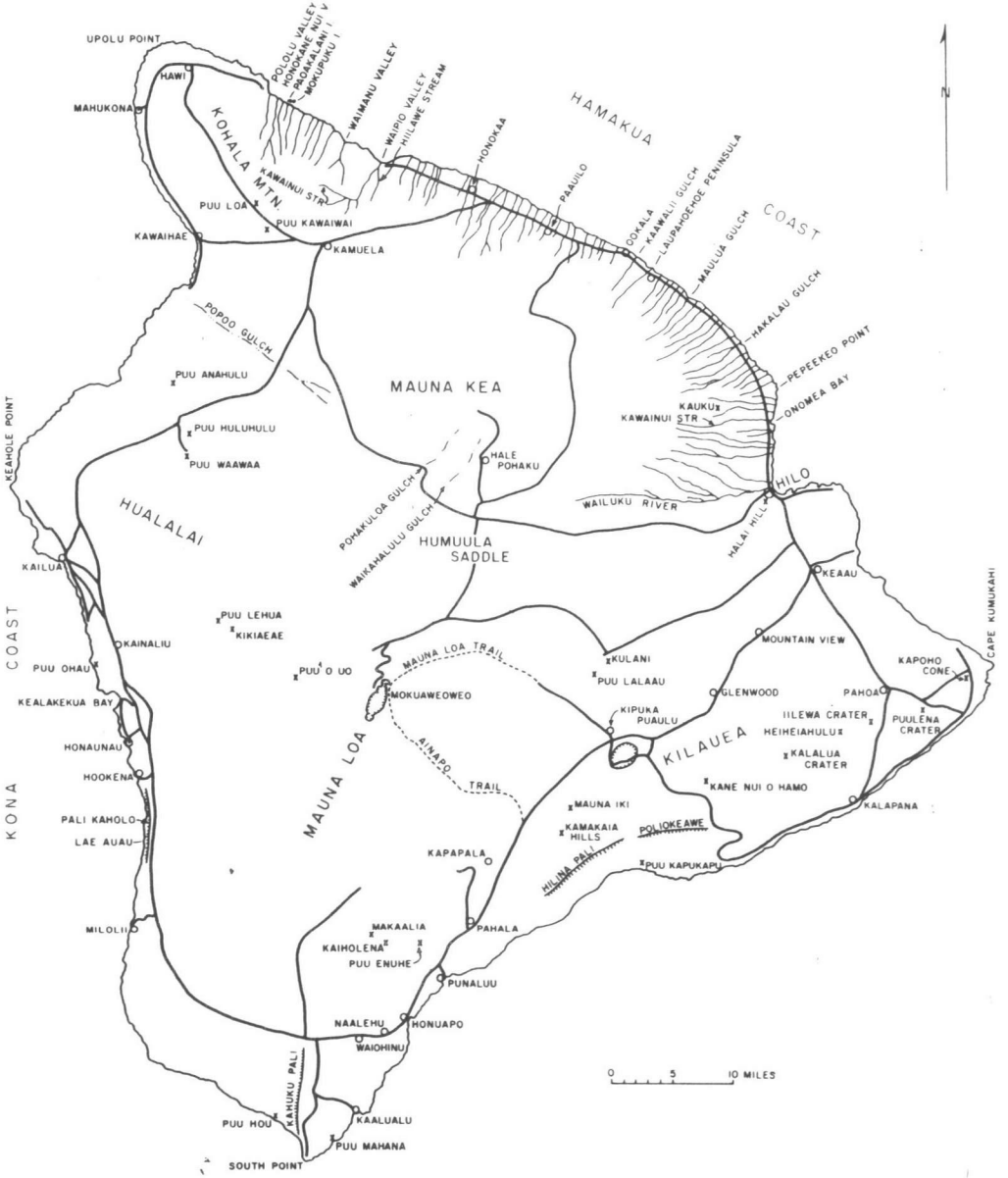


Figure 177. Map of the island of Hawaii, showing the location of places mentioned in the text.

Hualalai, on the west side of the island, is a dormant volcano that last erupted in the years 1800–1801. At that time two lava flows poured into the sea, burying the old Hawaiian trail near the coast and destroying at least one village. The rocks of Hualalai are in a less advanced stage of magmatic evolution than those of Mauna Kea, and a more advanced stage than those of Mauna Loa. Consequently, the mountain probably started to grow upward from the sea floor at a time between the beginnings of its two larger neighbors, though probably not before the start of the Ninole volcano. We do not know as yet how uniform are the rates of growth of individual volcanoes or how uniform are the rates of evolutionary change of magma composition.

Since 1801 Hualalai has been dormant, but a series of several thousand earthquakes came from beneath its northern flank in 1929, and occasional other earthquakes indicate that its magmatic hearth is still alive. We may expect the volcano to erupt again, but perhaps not for many decades. The appearance of the lava flows on the flank of Hualalai suggests that, during the latter part of the life of the volcano, eruptions have been rather infrequent, perhaps at intervals of a few hundred years.

When the Ninole volcano became extinct, activity appears to have shifted to two other centers, one beneath the present summit of Mauna Loa and the other 18 miles or so to the east, around both of which broad shield volcanoes were built. Toward the end of the history of the eastern shield volcano, the explosiveness of the eruptions increased somewhat and large tephra cones were built. These cones, Kulani cone and Puu Lalaau, stand near the summit of the eastern shield, which can be referred to as the Kulani shield volcano. The activity of the Kulani shield came to an end probably not more than a few tens of thousands of years ago. The more westerly shield has continued active and has built the present summit of Mauna Loa. Its lavas have now nearly buried the Ninole and Kulani volcanoes. Although Mauna Loa has continued to erupt frequently during the 19th and first half of the 20th centuries, it must already have grown to nearly its present size by the end of the Ice Age. Lava flows from Mauna Kea that are earlier than the end of the last glacial period descend southward into the Humuula Saddle between Mauna Kea and Mauna Loa and there turn sharply eastward or westward, showing that they must have been diverted by the obstacle of Mauna Loa, and this in turn indicates that the slope of Mauna Loa must have been in essentially its present position when these flows were erupted.

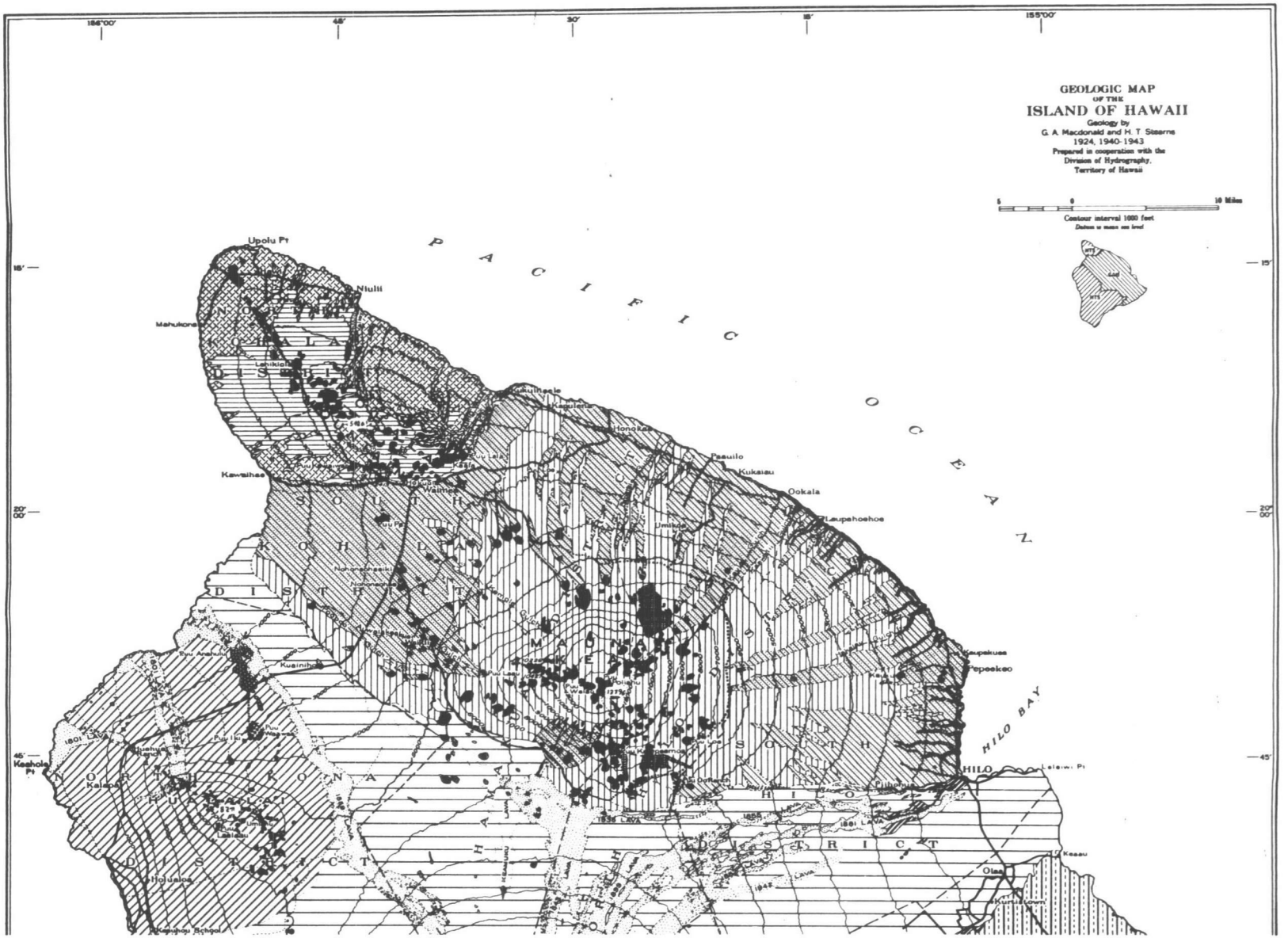
The volume of Mauna Loa, including the buried Ninole shield, is on the order of 10,000 cubic miles, making it probably the largest volcanic mountain on earth. However, at the rate that lava has been poured out by Mauna Loa during historic time, this entire bulk, from the ocean floor up, could have been produced in a little more than a million years.

Kilauea volcano forms only a slight protuberance on the southeast flank of Mauna Loa (fig. 189), but it appears to be a completely independent volcano. Along the boundary northeast of the summit of Kilauea its lavas interfinger with those from the present Mauna Loa. At a depth of only a few tens to hundreds of feet, however, they probably rest on the flank of the Kulani shield. There has been little correlation between the activities of Kilauea and Mauna Loa during historic time, and the magmas erupted at the two centers have reached slightly different stages of evolution, indicating that the two volcanoes are fed from different magma bodies at depth. True, there have been a few instances when the level of lava in the Halemaumau lake dropped abruptly at the time of an outbreak of Mauna Loa, and in 1868 the two volcanoes erupted nearly simultaneously, but in most instances eruption of one has caused no apparent reaction at the other. More than a century ago the great American geologist, James Dwight Dana, pointed out that the great difference in level of the two eruptive centers, one 13,000 feet above sea level and the other less than 4,000, precludes any direct connection of the two in a common magma chamber at shallow depth. If any connection exists, it must be deep and indirect. Recent unpublished work by J. G. Moore indicates that the average rate of production of lava in the southern Hawaii region has remained about the same despite the fact that from 1934 to 1950 all of the eruptive activity was at Mauna Loa, and since then all of it has been at Kilauea. This suggests that magma is being formed at a fairly constant rate in the earth's mantle, but that for some unknown reason the upward feeding of magma has changed, for the time being, from the Mauna Loa reservoir to that of Kilauea.

PAHALA ASH

Near the town of Pahala the remnants of the Ninole volcano are covered with more than 50 feet of yellowish volcanic ash, known as Pahala ash. What appears to be the same ash is found in many parts of the island—just below the top of the Hilina Pali on the southern slope of Kilauea, buried by younger Kilauea lavas; capping lavas of the Kahuku Volcanic Series on the slope of the Kulani shield northeast of Kilauea, where it has been buried by later lavas of Mauna Loa; and on Mauna Kea and Kohala Mountain (figs. 178, 179).

Most of the Pahala ash consisted originally of vitric ash—bits of Pele's hair, Pele's tears, and fragments of pumice thrown into the air by lava fountains and carried by the wind, like the material produced by the great lava fountains of the 1949 eruption of Mauna Loa and the 1959 eruption of Kilauea. Throughout most of its extent the once-glassy ash has been largely altered by weathering to a mixture of clay minerals and hydrated oxides of aluminum and iron. (The reddish brown to yellow, altered material somewhat resembles that of the tuff


GEOLOGIC MAP
OF THE
ISLAND OF HAWAII
Geology by
G. A. Macdonald and H. T. Stearns
1924, 1940-1943
Prepared in cooperation with the
Division of Hydrography,
Territory of Hawaii
Contour interval 1000 feet
Datum is mean sea level
10 Miles
PACIFIC OCEAN
HILO BAY
HILO
Upolu Pt
Niulii
Mahukona
Kawaihae
Honoka
Pauilo
Kukuau
Ookala
Laupahoehoe
Kapukua
Pepeekeo
Kaalaiki
Kaalaiki Pt
Kealakekua
Holualoa
Kainaliu
Kuainihi
Keaau
Olaa
Lalaiwi Pt
NORTH KOHALA DISTRICT
SOUTH KOHALA DISTRICT
NORTH KONA DISTRICT
SOUTH KONA DISTRICT
HILO DISTRICT
PUNA DISTRICT
MAUNA KEA
MAUNA LOA
1801 LAVA
1855 LAVA
1859 LAVA
1881 LAVA
1942 LAVA
155°00'
15'
30'
45'
156°00'
20° 00'
19° 45'

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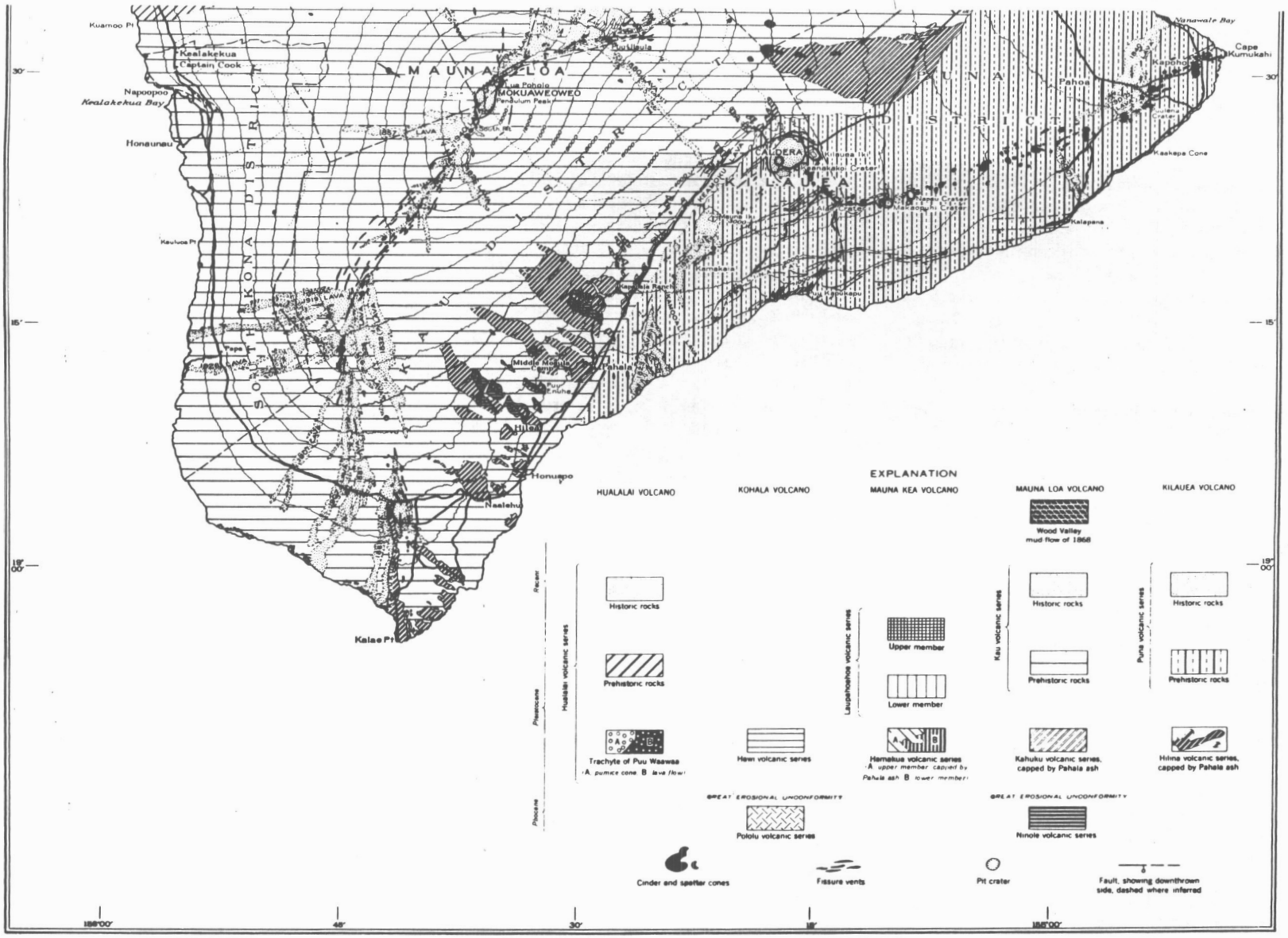

Kuamoo Pt
Kealakekua
Captain Cook
Napoopoo
Kealakekua Bay
Honaunau
Kaulwa Pt
Kalae Pt
SOUTH KONA DISTRICT
MAUNA LOA
Pua Pahala
MOKUAWEOWEO
Pendulum Peak
1852 LAVA
Tapa
1919 LAVA
Middle Maniu Crater
Puu Enuhe
Hilina
Honuapo
Nealehu
Kapapala
Pahala
Naalehu
Nanawale Bay
Cape Kumukahi
Kapoho
PUNA DISTRICT
Pahoa
CALDERA
KILAUEA
Kilauea Iki Crater
Halemaumau Crater
Kaakepa Cone
Kalapana
Kaluapele
Hilina Pali
Koae Fault System
Kau Desert
Ka'u Desert
Pahala Ridge
Kipuka Kahuku
Kahuku Ranch
Kahuku
Kamakaia
Kamakaia Pali
Kipuka Kaapuna
Kipuka Kapapala
Kipuka Ainahou
Kipuka Kaaha

cones of Oahu, and both have been called palagonite.) As a result of alteration it is usually impossible to determine the original composition of the material, and so the source of much of this ash is uncertain. Furthermore, it probably was erupted over a considerable span of time, and Pahala ash in one area may not be strictly coeval with that in another area.

Several different sources probably have contributed to the deposits of Pahala ash. On the flanks of Mauna Kea just north of the Wailuku River, the ash layer is more than 20 feet thick, while across the eastern and northern flanks of the mountain it becomes progressively thinner.

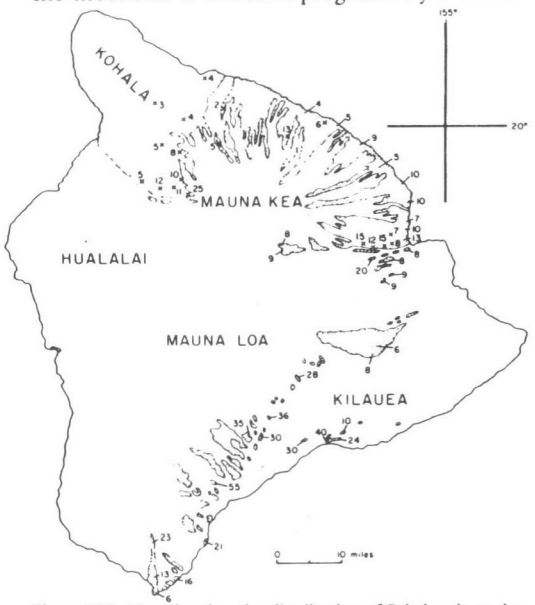


Figure 179. Map showing the distribution of Pahala ash on the island of Hawaii. The numerals indicate the approximate thickness of the ash at different points. (After Stearns and Macdonald, 1946.)

On the dry northwestern flank near Kamuela, some of the ash is quite fresh and has the same composition as late lavas of Mauna Kea. It is believed that most of the ash on Mauna Kea came from eruptions on that mountain, and that the ash layer becomes thinner toward the north because the trade winds carried most of the ash southwestward from the erupting vents. South of the Wailuku River, where it is found in water-development tunnels beneath the Mauna Loa lavas, the ash layer again becomes thinner, and on the flanks of the Kulani shield near Glenwood it is only 8 feet thick. These facts suggest very strongly that much of the ash on the east slope of Mauna Loa also came from vents on Mauna Kea. However, to the leeward of Kilauea, near Pahala, the ash is much thicker than to windward, and it seems certain that much of the ash southwest of Kilauea caldera came from Kilauea. Undoubtedly, some contributions also have been made by eruptions on Mauna Loa and Hualalai.

The Pahala ash is the only rock formation that is found on more than one of the volcanic mountains, and consequently, until more potassium-argon ages are obtained, it provides the only direct means of correlating the times of activity of the different volcanoes. Unfortunately, however, there is no certainty that the Pahala ash is everywhere of exactly the same age. It represents the total accumulation of all ash falling in a given area during an interval that was not interrupted by lava flows, and, in places where it has not been covered, its thickness is still increasing. For example, thin ash layers that overlie lavas of the Laupahoehoe Series on Mauna Kea form the top of the Pahala ash in adjacent areas that have not been covered by the Laupahoehoe lavas, and yet they are generally indistinguishable from the underlying ash. Areas mapped as Pahala ash on the eastern slopes of Mauna Kea and Mauna Loa are distinguished from adjacent ash-covered areas only by the greater thickness of the ash. There does, however, seem to have been a general period of abundant ash formation, when most of the Pahala ash was deposited essentially simultaneously over much or all of the island. This probably was the period of greatest activity of the late Hamakua and Laupahoehoe cones on Mauna Kea, and strong lava fountains at Kilauea, while fault scarps shielded the southern slope of Kilauea and the southeastern slope of Mauna Loa from lava flows, and only occasional flows invaded the eastern slope of the quiescent Kulani shield.

All of the rocks of the Kohala and Ninole volcanoes are older than the Pahala ash. On Mauna Kea most of the ash is older than the late lavas (Laupahoehoe Volcanic Series), but a thin layer of ash covers even the late lavas, as would be expected if the eruptions that produced these lavas were also the source of the ash. On the east flank of Mauna Loa the ash rests on, and is therefore younger than, the rocks of the Kulani shield. The lavas of the present Mauna Loa appear to be mostly younger than the ash, although in the region northeast of Mountain View, layers of ash are interleaved with lava flows, and the earliest Mauna Loa lavas in that area are probably coeval with the main period of formation of the Pahala ash. Ash resembling the Pahala ash is exposed also in the sea cliff at Kealakekua Bay, on the west flank of Mauna Loa, resting on pre-Mauna Loa lavas that may belong to either the Ninole volcano or an early phase of Hualalai volcano. Pahala ash is totally absent on Hualalai itself; all of the surface lavas there are younger than the ash. The Pahala ash which is exposed in the Hilina Pali on the south slope of Kilauea, is overlain by a cap of Kilauea lavas generally less than 100 feet thick. Other thin beds of ash lie between the underlying, older lava beds. A layer of ash formerly exposed at the base of the west wall of Kilauea caldera (but buried by the lava flow of 1919) probably was also Pahala ash. If so, the present Kilauea lavas form a cap, with a maximum thickness of only about 400 feet, overlying the Pahala ash. Thus, the main period of deposition of the Pahala ash was later than the Kohala, Ninole, and Kulani volcanoes; it was contemporaneous with the late lavas of Mauna Kea and some of those of Mauna Loa; and it appears to mark the beginning of the present phase of Kilauea.

The approximate time relationships of the rocks of the different volcanoes are shown in figure 180.

KOHALA MOUNTAIN

The northern end of the island of Hawaii, known as Kohala Mountain (fig. 176), consists of an oval shield volcano built around two rift zones that trend northwestward and southeastward from the summit region (figs. 182, 189). The last eruptions were moderately explosive and formed a series of large cinder cones that stud the surface of the shield. The top of the highest cone is 5,480 feet above sea level.

On the western and northern sides of Kohala Mountain erosion has made little headway (figs. 181, 184). The deepest stream-cut gulches are less than 100 feet deep, and the mountainside is essentially the original land surface built by the volcano. The sea cliff along its margin is less than 50 feet high. This gentle topography stands in marked contrast to the topography of the northeastern side. There, much of the original constructional slope has been cut away, and the shield is truncated by a series of great sea cliffs reaching heights of 1,400 feet, notched by canyons 1,000 to 2,500 feet deep (figs. 181, 183, 185). The canyons were once even deeper. Near their mouths the bottoms are now flat floors of alluvium, deposited as a result of a recent rise of sea level relative to the land. The thickness of the alluvial fill is not known, but near the valley mouths it is probably about 300 feet. Paoakalani and Mokupuku islets, off the northeastern shore of Kohala, are sea stacks left by wave erosion of the surrounding rocks. The northeastern shore of Kohala between Waipio and Pololu valleys appears to have been cut back nearly a mile by wave erosion. The difference in the degree of erosion of the northeastern and southwestern slopes of Kohala is explained partly by the heavier rainfall and stronger wave attack on the northeastern side, but largely by the structure of the volcano, described later.

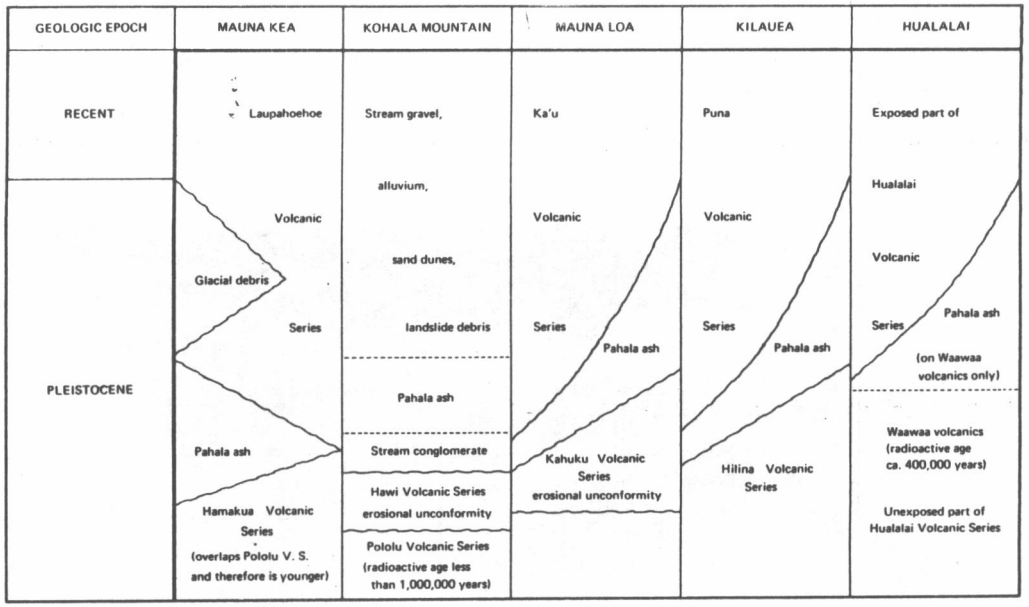


Figure 180. Diagram showing principal rock units on the island of Hawaii. All rock units thus far investigated have normal magnetization, and the oldest radioactive dates determined are less than 1,000,000 years, so that it appears unlikely that any exposed rocks are older than Pleistocene.

The rocks of the Kohala volcano have been divided into two series (Stearns and Macdonald, 1946, pp. 170–180). The older, Pololu Volcanic Series consists very largely of flows of basalt, each one usually 5 to 20 feet thick, and rarely reaching as much as 50 feet. Successions of these lavas 2,000 feet thick are exposed in the walls of the deep canyons (fig. 178), and they extend on down below sea level probably all the way to the ocean floor. Through most of the succession, ash layers are rarely found, but near the top of the series they become more numerous. At about the same level another change occurs. The lower, main part of the series is made up of tholeiitic basalt, tholeiitic olivine basalt, and oceanite, but in the upper part alkalic olivine basalts appear. Some of the flows in the upper part of the tholeiitic part of the series contain very abundant large crystals (phenocrysts) of labradorite feldspar. The lava beds of the Pololu Series are especially well exposed along the trail down the southeast side of Waipio Valley.

The younger, Hawi Volcanic Series is separated from the rocks of the Pololu Series by an eroded surface (unconformity), with valleys as deep as 300 feet, covered with red soil and in places underlain by as much as 50 feet of decomposed, weathered rock. The unconformity marks a long period of time during which the volcano was either completely inactive or erupted only very infrequently. The lavas of the Hawi Series, above the unconformity, are mostly mugearite, but a few flows and domes of trachyte are known and one flow of hawaiite has been found at the northwestern shore, near Mahukona. (Some of the rocks are transitional between mugearite and trachyte, and have been referred to as "benmoreite.") Thin beds of ash, partly weathered to soil, lie between flows of the Hawi Series at some places, and elsewhere the flows are separated by lenticular deposits of gravel laid down by

streams in shallow gullies. Much longer intervals of time must have elapsed between eruptions of the Hawi Series than between those of the main part of the Pololu Series. The rocks of the Hawi Series are best seen along the highway from Kamuela to Hawi.

The deep highway cut just southwest of Puu Loa, 5 miles beyond the junction with the road to Kawaihae, is in a thick short flow of "benmoreite," erupted at Puu Loa, which is a cinder cone built at the vent. Puu Kawaiwai, on the lower side of the road 3 miles beyond the same junction, is a cinder cone of hawaiite composition. The magma for the Kawaiwai eruption may have come from the reservoir beneath Mauna Kea, and been guided to the surface by a fissure that cut the flank of the adjacent Kohala volcano; or, like the lava flow near Mahukona, it may be simply a variant of the magma from the Kohala reservoir.

The focus of the Kohala volcano lay near the present summit of the mountain. A series of curved faults in that region suggests that a caldera probably was formed in the summit of the shield near the end of the eruption of the Pololu Series, but it has been entirely buried by lavas of the Hawi Series. However, the massive filling of a pit crater a mile in diameter can be seen near the head of the canyon of Kawainui Stream. The exposed part of the crater fill is 2,000 feet thick and consists mostly of dense flows of tholeiitic basalt up to 100 feet thick. At the western side the lavas rest on talus breccia that accumulated at the foot of the crater wall.

The geologic map (fig. 178) shows that lavas of the Hawi Series are absent for a stretch of 7 miles on the northeast slope of the mountain between Waimanu and Honokane Nui valleys. There, the Hawi lavas were prevented from flowing northeastward by a series of fault scarps in the summit region. Either at the end of the formation of the main shield or early in the period of eruption of the Hawi lavas, a northwest-trending graben 6 miles long and 1

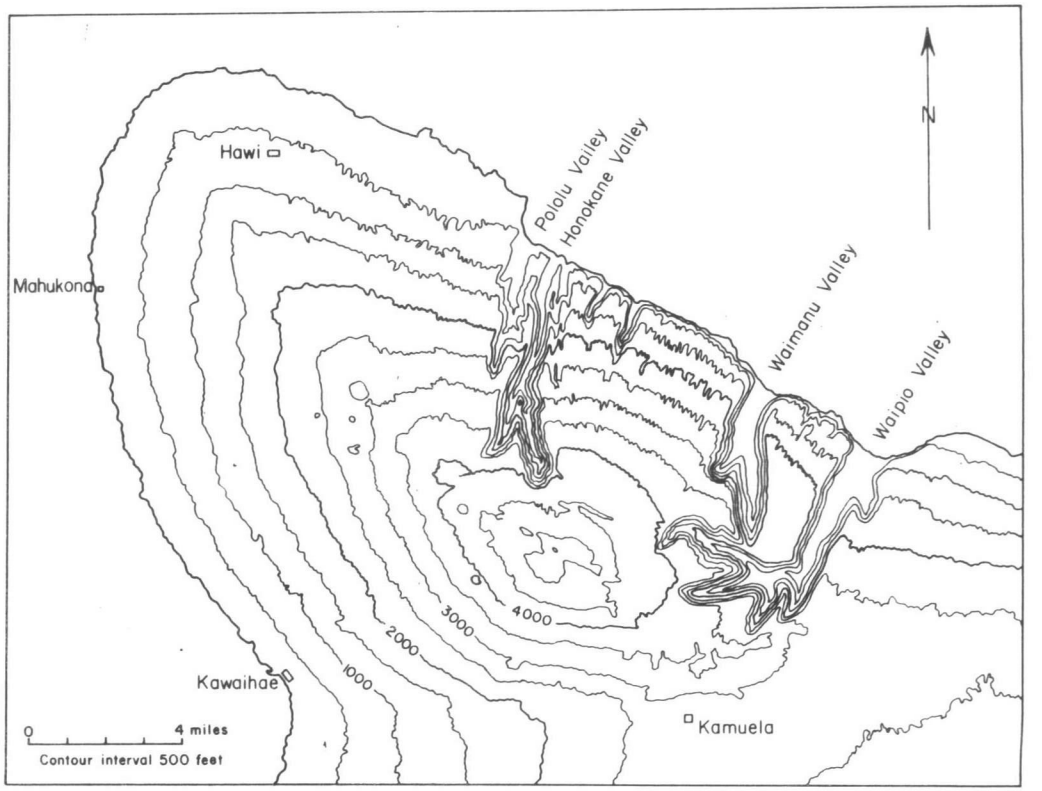


Figure 181. Map of Kohala Mountain, showing the huge valleys cut into the windward (northeastern) slope, and the small degree of dissection of the leeward slope.

to 3 miles wide formed across the top of the volcano. Lavas erupted within this graben gradually filled it, escaping from it at the northwest and southeast ends and eventually overflowing much of its southwestern rim, but on the northeast side the bounding fault scarps were higher and were never overtopped by the flows. Consequently, although on the western and northern slopes erosion was constantly interrupted and its damages repaired by repeated lava flows of the Hawi Series, on the northeastern slope it went on undisturbed, and huge valleys were cut. To this long period of uninterrupted erosion, even more than to the higher rainfall, is due the much greater erosional dissection of the northeast side of Kohala Mountain. Eventually, however, lava spilled over the fault scarp at the northern end of the graben and poured into the head of Pololu Valley (fig. 186).

The great valleys of the northeastern side of Kohala Mountain differ in two marked respects from the usual radial valleys of the Hawaiian Islands. Waipio Valley extends inland southwestward, and then makes an abrupt right-angle bend toward the northwest (fig. 185). Waimanu Valley also extends inland southwestward, and ends in a deep, streamless, V-shaped notch (a wind gap) high on the northeastern

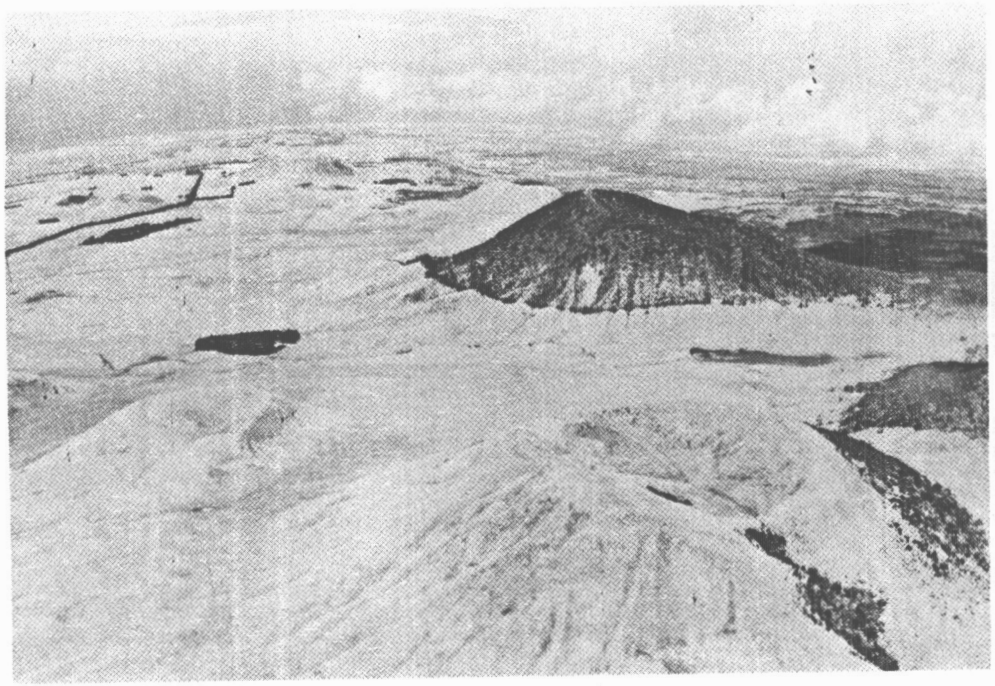
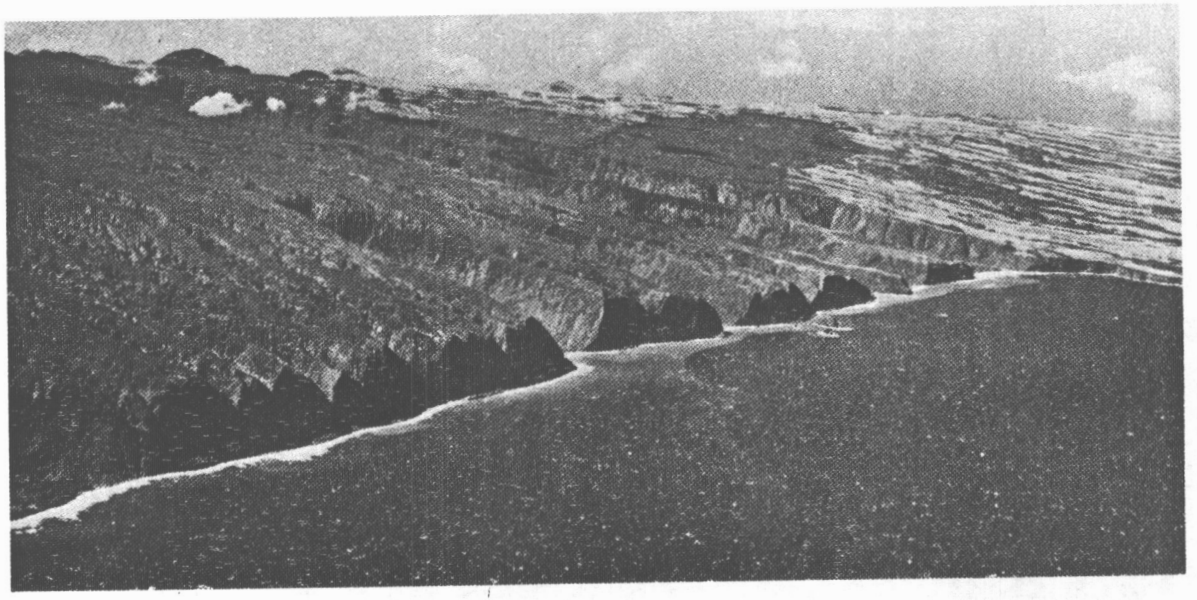


Figure 182. Andesitic cinder cones of the Hawi Volcanic Series mark the trend of the northwest rift zone on Kohala Mountain, Hawaii. The largest cone is about 700 feet high.

Figure 183. Sea cliff cut across lavas of the Pololu Volcanic Series on the northeastern side of Kohala Volcano, Hawaii. The straight line of the cliff and the faceted spurs suggest a fault origin for this coastline, but there is no other evidence that it is not entirely the result of erosion. The floors of the larger valleys are close to sea level, but the smaller valleys are "hanging" and their streams enter the ocean as waterfalls. Beyond Pololu Valley, at the right-hand end of the high sea cliff, the long gentle slope is formed by later lavas of the Hawi Volcanic Series. Note the much smaller degree of dissection of the Hawi lavas as compared with the Pololu lavas in the center of the photograph.



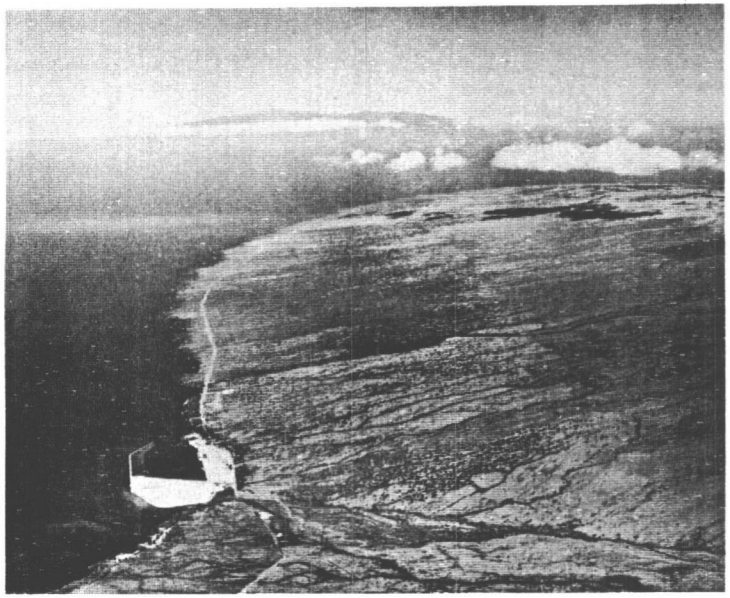


Figure 184. Northwestern slope of Kohala volcano, Hawaii. Contrast the much smaller degree of dissection on this drier and younger side of Kohala with that on the wet northeastern side of the mountain shown in figures 183 and 185. The port of Kawaihae lies in the foreground, and the summit of Haleakala, on Maui, looms in the distance.

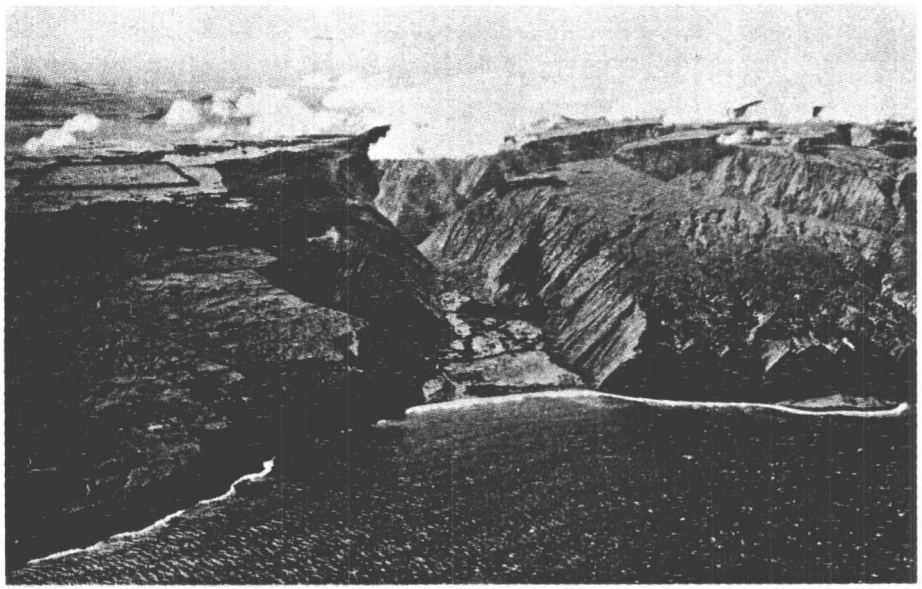


Figure 185. Waipio Valley, Hawaii. The wide flat floor of the valley is the result of submergence of a stream-cut valley due to relative rise of sea level, and the filling of the valley by alluvium and possibly marine sediments. Sea level probably was about 300 feet lower than now when the valley was cut. The head of Waipio Valley, following a fault zone, bends sharply to the right and has captured the principal former tributaries of Waimanu Stream. The head of Waimanu Valley and the streamless notch (wind gap) separating it from the head of Waipio Valley are visible at the right of the photograph. Note the lateral capture by Waipio Stream of parallel consequent streams, and the vertical grooves cut in the side of the main valley by the captured streams plunging down to the valley floor. The low peninsula at the foot of the sea cliff to the right of Waipio Valley was formed by a landslide from the cliff.

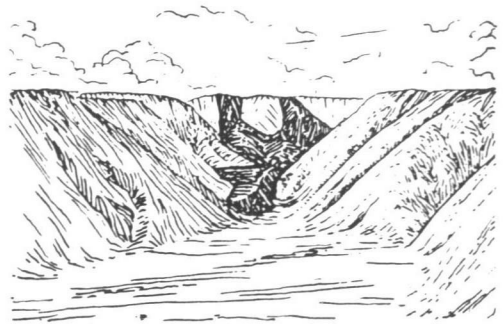


Figure 186. Sketch of Pololu Valley, Kohala Mountain, showing the flow of mugearite that poured into the head of the valley. (From Stearns and Macdonald, 1946.)

wall of the northwest-trending portion of Waipio Valley (fig. 181). The notch is clearly the result of cutting by Waimanu Stream during earlier times, and formerly the stream and canyon must have extended farther inland. Kawainui Stream was once the headwaters of Waimanu, but has been captured by the faster-cutting Waipio Stream, robbing Waimanu Stream of much of its water. Mass transfer (chap. 10) continues on the walls of upper Waimanu Canyon, but the stream is no longer adequate to carry away all the debris that reaches the valley bottom, and the head of the canyon is becoming clogged with landslide and other debris. The northwesterly trend of the upper part of Waipio Canyon is the result of the same series of graben-boundary faults mentioned in the last paragraph, which prevented the streams, as well as the lava flows, from flowing northeastward.

The late activity of Kohala volcano was contemporaneous with the later part of the building of the main shield of Mauna Kea. Lava flows of the Hawi Series interfinger with lavas of Mauna Kea in the sea cliff east of the mouth of Waipio Valley. However, Mauna Kea continued active long after the death of the Kohala volcano. The canyons of Kohala Mountain had already reached nearly their present size by the time of eruption of the late lava flows of Mauna Kea (lava flows that were considerably more recent than the building of the main Mauna Kea shield). One of the late Mauna Kea flows poured over the headwall of Hiilawe Canyon, a tributary of Waipio Valley, and filled the canyon to a depth of about 150 feet. The flow has since been cut through by the stream to the level of the old canyon floor.

MAUNA KEA

Mauna Kea volcano passed through the primitive shield-building stage into the late stage, and produced a cap of differentiated lavas that almost completely buried the original shield above sea level. The rocks have been divided into an older Hamakua Volcanic Series and a younger Laupahoehoe Volcanic Series (fig. 178), and the former has been further divided into upper and lower members. The lower member of the Hamakua Series comprises the tholeiitic basalts, olivine basalts, and oceanites of the early shield-building stage. It is exposed only in the lower part of the sea cliffs along the Hamakua Coast north of Hilo (fig. 187). The rocks are the usual thin beds of pahoehoe and aa, like those of Mauna Loa and Kilauea. They pass upward gradationally into alkalic olivine basalts, hawaiites, and ankaramites that make up the upper member of the series. The rocks of the upper member are well exposed in highway cuts along the Hamakua Coast. They are covered by a layer of Pahala ash that reaches a thickness of 25 feet along the Wailuku River above Hilo but gradually thins northward to about 6 feet near Paauilo (fig. 179). Along the Hamakua Coast the ash is much altered, to a mixture of clay minerals and aluminum and iron oxides. The structure of the fragments composing the ash is still sufficiently preserved, however, to show that they were originally fragments of pumice and cinder and finer glassy debris from Strombolian- or Hawaiian-type eruptions. Layers of similar ash, a few inches thick, lie between the lava beds of the underlying upper member of the Hamakua Series.

The maximum thickness of the Pahala ash is found only on the lower slopes of Mauna Kea. On the upper slopes its accumulation was repeatedly interrupted by lava flows of the Laupahoehoe Series, and the ash consists of several thin beds between the flows. The top of Mauna Kea consists almost wholly of rocks of the Laupahoehoe Series (figs. 178, 188). Rocks of the Hamakua Series are exposed only in Waikahalulu and Pohakuloa gulches on the south flank of the mountain (fig. 148), and in another, smaller gulch 2 miles farther west. The Laupahoehoe Series consists predominantly of hawaiite, with lesser amounts of alkalic olivine basalt and ankaramite. Hawaiite flows are well exposed along the highway between Honokaa and Kamuela, and south of Popoo Gulch on the road to Kona. They are thick, with very hummocky tops. In the highway cuts, the massive flow centers are seen to be underlain and overlain by fragmental portions in which the fragments are less spinose and more regularly shaped than those of typical aa, and grade toward the shapes characteristic of block lava flows. The three latest flows of the Laupahoehoe Series bury glacial moraines, yet they show no signs of having been erupted beneath ice, and hence must have been erupted within the last 15,000 years.

Eruptions of the Laupahoehoe Series were almost wholly restricted to the upper slopes of the volcano. One small eruption of alkalic basalt on the lower slope, near Ookala, formed a small dome and a stubby lava flow. Most of the eruptions were of Strombolian type and built big cinder cones, some of them more than a mile across at the base and several hundred feet high. Good exposures of the internal structure of cinder cones are provided by cinder quarries in some of the cones along the road through the Humuula Saddle, between Mauna Kea and Mauna Loa. Large cones south of the road are Mauna Kea cinder cones projecting through later lava flows of Mauna Loa. The cones just west of Hale Pohaku, at 9,500 feet altitude on the south slope of Mauna Kea, and some cones elsewhere on the mountain, contain numerous cored bombs in which the cores are fragments of peridotite and gabbro brought up from depth.

The broad shield volcano built in the early stages of Mauna Kea is surmounted by a steeper-sided cone formed by the rocks of the Laupahoehoe Series and the upper member of the Hamakua Series. The general form of the shield is still clearly visible on the lower slopes, particularly from viewpoints on Halai Hill and

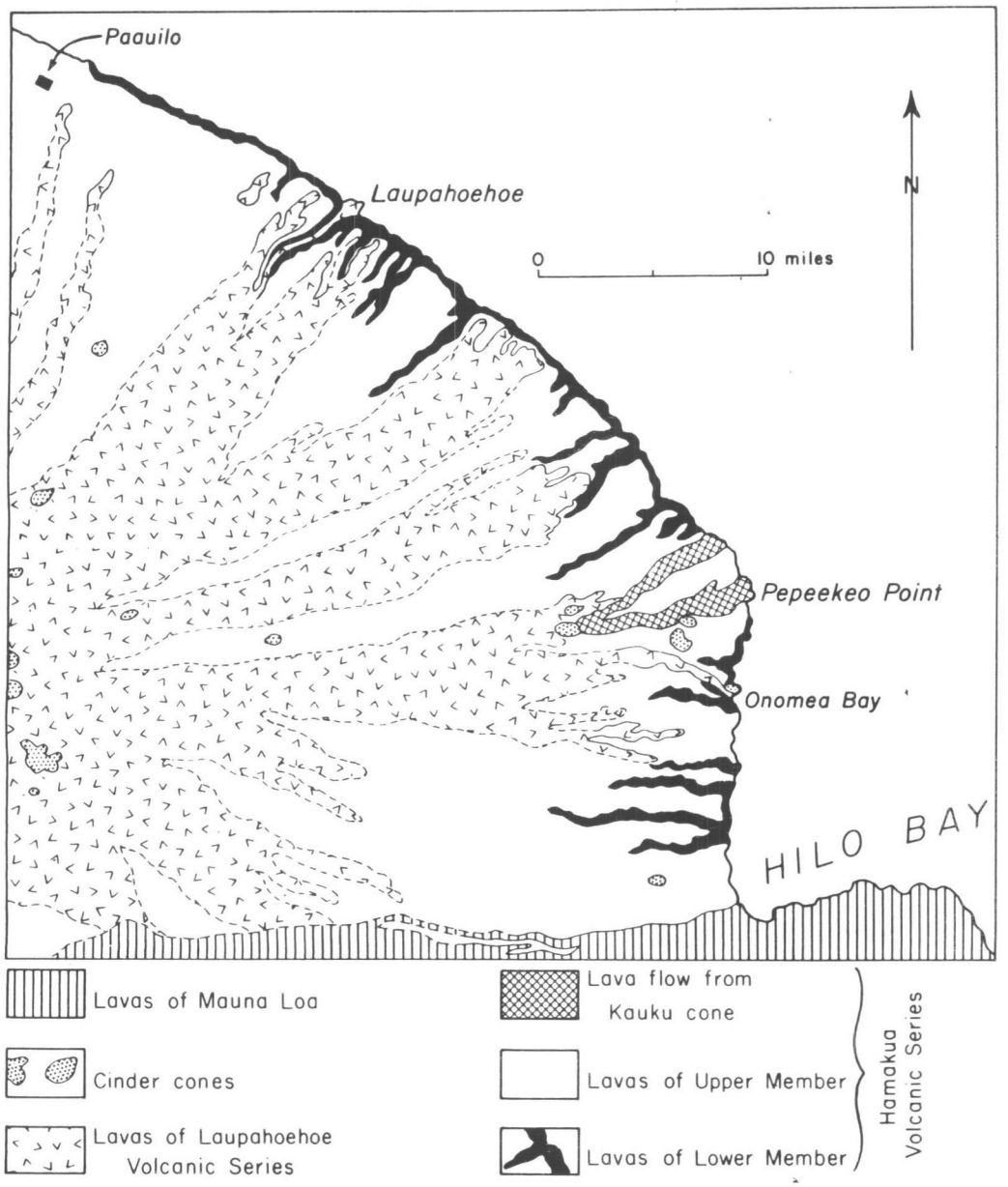


Figure 187. Map showing distribution of rock series on the eastern slope of Mauna Kea. (After Stearns and Macdonald, 1946.)

along the shore east of Hilo. Whether or not a caldera was present at the top of the shield is uncertain. However, some of the cones of the Laupahoehoe Series are situated along lines which curve around the summit of the mountain and probably were controlled by concentric fractures similar to those that bound calderas (fig. 87). Probably a former caldera does lie buried beneath the later lavas.

The rift zones now visible are less pronounced than they probably were in the earlier shield, but westerly and southerly rift zones are suggested by alignments of cinder cones of both the Laupahoehoe and Hamakua Series. An easterly rift zone (fig. 189) is suggested by a few late cones of the Hamakua Series, including the cones that have been extensively quarried near Pepeekeo and the cone remnant at the north side of Onomea Bay that formerly contained the Onomea sea arch (fig. 135). It is still more clearly indicated by the broad ridge that extends eastward from Pepeekeo Point all the way to the deep ocean floor. Recent studies show that the lavas on this deep-sea ridge are tholeiitic basalts of the early Mauna Kea shield. Kauku ("the louse") is an appropriately named parasitic cone on the east rift zone from which issued a flow of ankaramite. The flow divided into two branches, both of which reached the sea. The more southerly branch forms Pepeekeo Point (fig. 187). The Kauku eruption was one of the last of the Hamakua Series.

Mauna Kea furnishes an excellent example of the influence of climate on erosion. The dry western slope is almost unscarred by erosion. In contrast, the northeastern slope, which is exposed to the trade-wind rains, has in the same span of time become trenched by canyons several hundred feet deep. Maulua Gulch is 650 feet deep a mile inland from its mouth, and Kaawalii Gulch is nearly as deep. Both were formerly deeper. The mouths of Maulua, Kaawalii, and Hakalau gulches are filled with

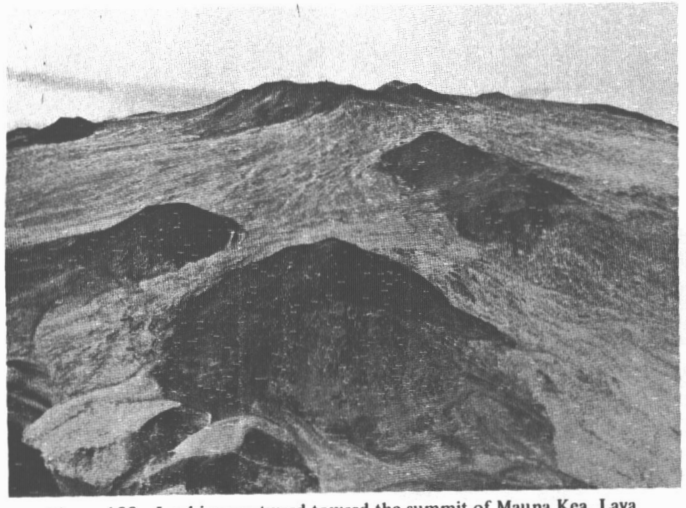


Figure 188. Looking westward toward the summit of Mauna Kea. Lava has issued from the flank of the cinder cone in the foreground and spread out fanwise. A similar fan of lava issued from the base of the Summit Cone in the distance.

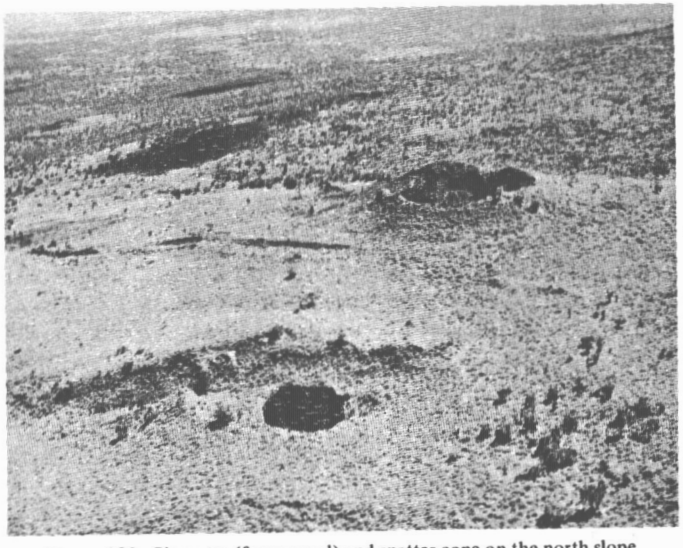


Figure 190. Pit crater (foreground) and spatter cone on the north slope of Hualalai volcano. A collapsed lava tube extends to the left between them.

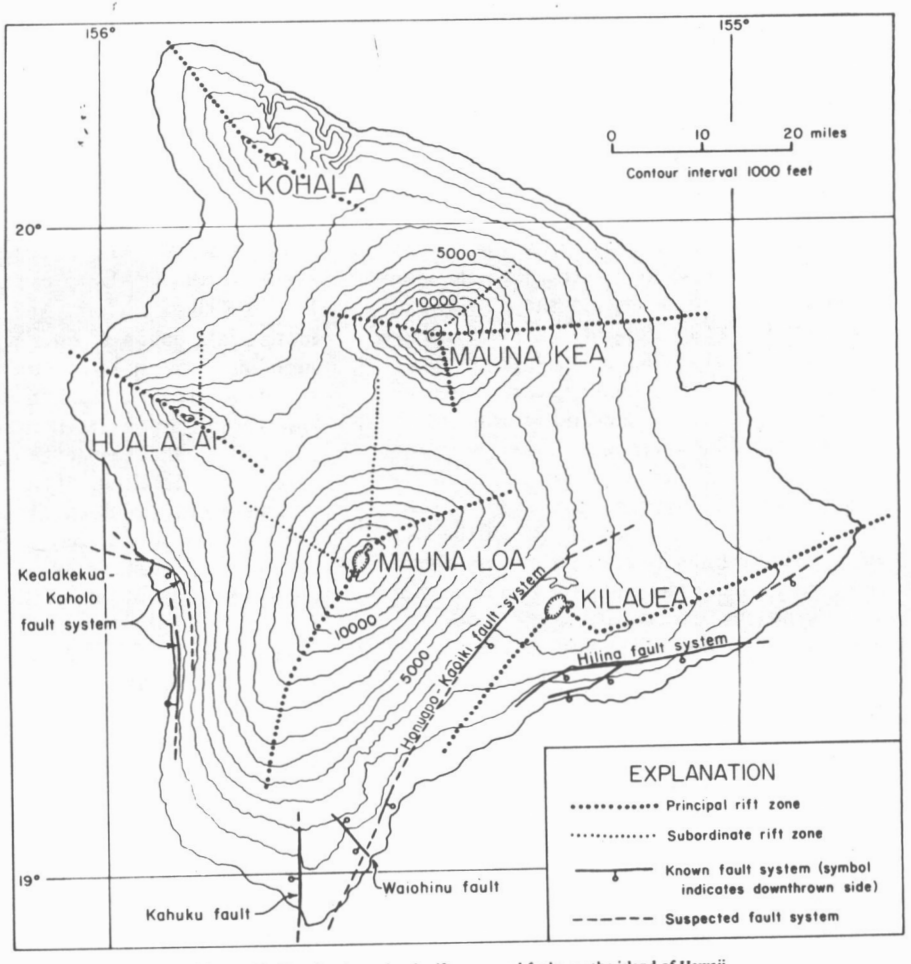


Figure 189. Map showing volcanic rift zones and faults on the island of Hawaii.

accumulations of stream-laid alluvium, deposited as a result of a recent rise of sea level. Laupahoehoe Gulch, cut into the rocks of the Hamakua Series, has been partly filled by a later flow of hawaiite of the Laupahoehoe Series. At the canyon mouth the flow spread out to form the flat-topped, delta-like Laupahoehoe Peninsula. A similar gulch once extended inland from Onomea Bay, along the course of the present Kawainui Stream. It also has been filled by a late lava flow of hawaiite. The channel of Kawainui Stream, with its magnificent display of potholes, follows approximately the former channel of the lava flow, and the hillocks adjacent to the stream mark the former levees along the lava river.

Between the occasional large gulches, the northeastern flank of Mauna Kea is barely beginning to show the scars of erosion (fig. 102). Even the largest gulches extend inland only 3 or 4 miles. The streams plunge into them over high waterfalls, the erosive action of which is gradually extending the canyons headward. Between the major gulches broad surfaces of Pahala ash are crossed only by shallow gullies. The large number of small streams are consequent on the original constructional slopes, and integration of the drainage into a smaller number of master stream systems is just beginning. Excellent examples of near capture of one stream by another can be seen from the air during flights between Hilo and Honolulu.

HUALALAI

The present shield of Hualalai volcano was built by eruptions from a well-defined rift zone that trends approximately N50°W across the summit (fig. 189). About 3 miles east of the summit this is intersected by a less well defined rift zone that trends nearly north-south, fanning out on the northern flank of the mountain. More than 100 small cinder and spatter cones (fig. 190) are scattered along these rift zones. The eruptions were much less explosive than the late eruptions of Mauna Kea and Kohala, and the cones built by them are smaller and contain a larger proportion of spatter. However, they were more explosive than those of Mauna Loa and Kilauea, as evidenced both by larger cones at the vents and by more abundant ash. At the summit of the mountain a collapse crater about a third of a mile across occupies the apex of a small lava shield. Scattered around it are angular blocks thrown out by a recent phreatic explosion. There is no direct evidence that a caldera ever existed on Hualalai. If it did, it has been completely buried by later lavas.

Hualalai appears to have just entered the late stage of the eruptive cycle. Nearly all of its lavas are alkalic olivine basalt, but a few flows are gradational to hawaiite. No tholeiitic basalts have been found, though presumably a tholeiitic shield lies buried beneath the alkalic cap. The flows are of both pahoehoe and aa types. They are especially well exposed in cuts along the highway between Kainaliu and Kailua. On this steep southwestern slope of the volcano the flows are thin, averaging only 4 or 5 feet in thickness. They must have been very fluid, and have flowed very rapidly.

Many of the lava flows contain scattered angular inclusions of bright green to brown peridotite, from a fraction of an inch to a foot across. They are especially abundant in the flow of 1800–1801, where they can be seen in cuts at the highway; but near the telephone relay station, about 2 miles upslope from the highway, they are present in tens of thousands. There the flow spread over a comparatively flat area and lost velocity, and the heavy inclusions tended to settle out like pebbles being dropped from a slowing stream of water. Most of the liquid drained out from between them, but left each fragment coated with a thin black layer of lava. The resulting accumulation of partly rounded, black to brown masses, each a few inches across, resembles more than anything else a heap of potatoes buried by the lava. In addition to peridotite there are also fragments of gabbro and rocks intermediate between gabbro and peridotite (picrite).

On the southern slope of Hualalai most of the lava flows are covered with a layer of ash. At the level of the highway it ranges from a few inches to about 2 feet thick, but it thickens upslope, and, southeast of the summit, there are areas several square miles in extent covered with ash and pumiceous cinder averaging 2 to 3 feet in depth.

On the north slope of Hualalai, 6 miles from the summit, Puu Waawaa is a large cone of trachyte pumice, more than a mile in diameter (figs. 178, 191*A*). A trachyte lava flow more than 900 feet thick extends 6 miles northward from the cone. The pumice of the cone (figs. 191, 192) is being quarried for lightweight concrete aggregate and insulating material. Scattered through the pumice are many blocks of black trachyte obsidian. The lava flow consisted of several flow units, each 250 to 500 feet thick. Seen from the southwest, the edges of some of these units form conspicuous terraces. The western edge is a steep escarpment 500 feet high. The eastern side of the flow has been completely buried by later basalt flows of Hualalai and Mauna Loa, and some of these have spread across the surface of the trachyte and cascaded down its western escarpment. The closest exposure of the trachyte flow is separated from its source cone by more than a mile of these later flows of basalt (fig. 191*B*). Where the surface of the trachyte flow is still exposed, it is very irregular and hummocky, with crescentic flow ridges up to 50 feet high, convex downstream. Puu Anahulu and Puu Huluhulu are simply high points on the irregular flow surface.

The Puu Waawaa trachyte represents a stage of magmatic differentiation far more advanced than that of any other rock of Hualalai. However, the cone lies squarely on the north rift zone of Hualalai and more than 20 miles from the nearest other occurrences of trachyte—on Kohala Mountain. The Waawaa trachyte was probably formed by differentia-

tion in a relatively small magma chamber belonging to Hualalai, but isolated from the main magma chamber of that volcano.

During the latter part of its history, Hualalai was active simultaneously with Mauna Loa, and the lava flows of the two volcanoes interfinger on both the southern and northeastern flanks of Hualalai. A short distance south of the edge of the Hualalai lavas (fig. 178), the small cones of Puu Lehua and Kikiaeae, at an altitude of 5,000–5,500 feet, may possibly be cinder and spatter cones on the north-south rift of Hualalai, surrounded by later lavas of Mauna Loa. However, since the eruptive fissures on which the cones were built trend N60°W and line up with another cone (Puu o Uo) still higher up the flank of Mauna Loa, the cones probably belong to Mauna Loa.

MAUNA LOA

As noted on a previous page, the present mass of Mauna Loa appears to be made up of at least three huge shield volcanoes built around three separate eruptive centers. The lavas of all of them are tholeiitic basalts, olivine basalts, and oceanites. It is not possible to determine the position of the rift zones of the Ninole shield, or whether it had a caldera, because all but a few small remnants of its southeastern flank have been buried by lavas from the present southwest rift of Mauna Loa.

The remnants of the Ninole shield (fig. 178) form a series of steep-sided hills projecting high above the surrounding gently sloping lava surface. The rocks, known as the Ninole Volcanic Series, consist of thin layers of pahoehoe and aa exposed in the sides of the hills. In one, Puu Enuhe, a layer of vitric tuff 2 to 12 feet thick is interbedded with the lavas about 500 feet below the top. A thickness of 2,100 feet of Ninole lavas is exposed in Makaalia hill. The hills represent the high parts of ridges that lay between valleys cut by streams into the Ninole shield. Their tops have remained unburied by lava flows ever since the extinction of the Ninole volcano, and they have received the full accumulation of Pahala ash, which reaches a thickness of 55 feet on Puu Enuhe and Kaiholena hill.

Little more is known about the structure of the Kulani shield, which likewise is nearly buried by lavas from Mauna Loa's northeast rift. Part of the eastern flank of the Kulani shield is still exposed, however, and a row of cones and pit craters extending nearly eastward from Kulani Cone appears to delineate part of its old rift zone. It has been found also that a zone of magnetic anomalies extending westward from the ocean east of Cape Kumukahi (East Cape) follows the projection of this rift zone—not the present rift of Kilauea (fig. 173). Much of the eastward bulge of the island of Hawaii may be due to the Kulani shield, with only a thin cover of Kilauea lavas.

The main evidence for the existence of the Kulani shield is physiographic. Viewed from the summit of Kilauea, the flank of Mauna Loa exhibits a distinct terrace, or bench, which slopes gradually southwestward from a point south of Kulani Cone and finally disappears near Kapapala. The southeastern edge of the terrace is the Kaoiki fault scarp, and the northwestern edge is the beginning of the steeper rise of the present Mauna Loa shield. There seems to be no way to account for the terrace except as a remnant of an older, buried topography. It is crossed by many recent lavas of Mauna Loa, which, however, have left many kipukas ("islands") of older rock, capped by Pahala ash. Kipuka Puaulu (Bird Park), 2 miles northwest of Kilauea caldera, is one of these.

The large triangular kipuka east of Kulani Cone (fig. 178) is part of the flank of the Kulani shield that has been sheltered from later lava flows by the cone, and a similar, but smaller, kipuka lies just to the north. These segments of the shield surface also are covered with Pahala ash.

On the southern slope of Mauna Loa, from Kapapala to South Point, a succession of large and small kipukas consist of tholeiitic lava flows covered by Pahala ash. These lavas and associated cones have been named the Kahuku Volcanic Series. They have buried the erosional topography formed on the older Ninole shield. The lavas are best seen in the Kahuku Pali (figs. 36, 193), a fault scarp that extends inland from South Point, where about 600 feet of interbedded aa and pahoehoe flows is exposed. Near the coast, the base of the series lies an unknown distance below sea level. The Kahuku lavas south of Kapapala appear to have come from the present southwest rift zone of Mauna Loa, and the rocks of the Kulani shield also are included in the Kahuku Series.

The rocks of the present Mauna Loa shield are known as the Ka'u Volcanic Series, which includes lavas of present-day eruptions. Nowhere has erosion cut deeply into the volcano, but the upper 600 feet of the series is visible in the wall of Mokuaweoweo caldera, at the summit of the mountain. Ash is almost absent in the exposed sections, which consist of interbedded pahoehoe and aa flow units averaging about 15 feet in individual thickness. The flows in the caldera walls slope gently outward, showing that they came from vents within the area of the present caldera which have been dropped down out of sight by the caldera collapse.

A blanket of pumice as much as 5 feet thick extends half a mile to leeward of the cinder and spatter cone of the 1949 eruption, on the southwest rim of the caldera (fig. 52); and small areas of pumice and vitric ash lie to leeward of some of the other recent cones. Thin layers of angular lava blocks and lithic ash, thrown out by small phreatic explosions, lie on the surface on the east rim of the caldera near the rest house, and on the northwest rim (fig. 47*B*). Another small patch of phreatic explosion debris lies along the Ainapo Trail 2.3 miles south of the rest house.

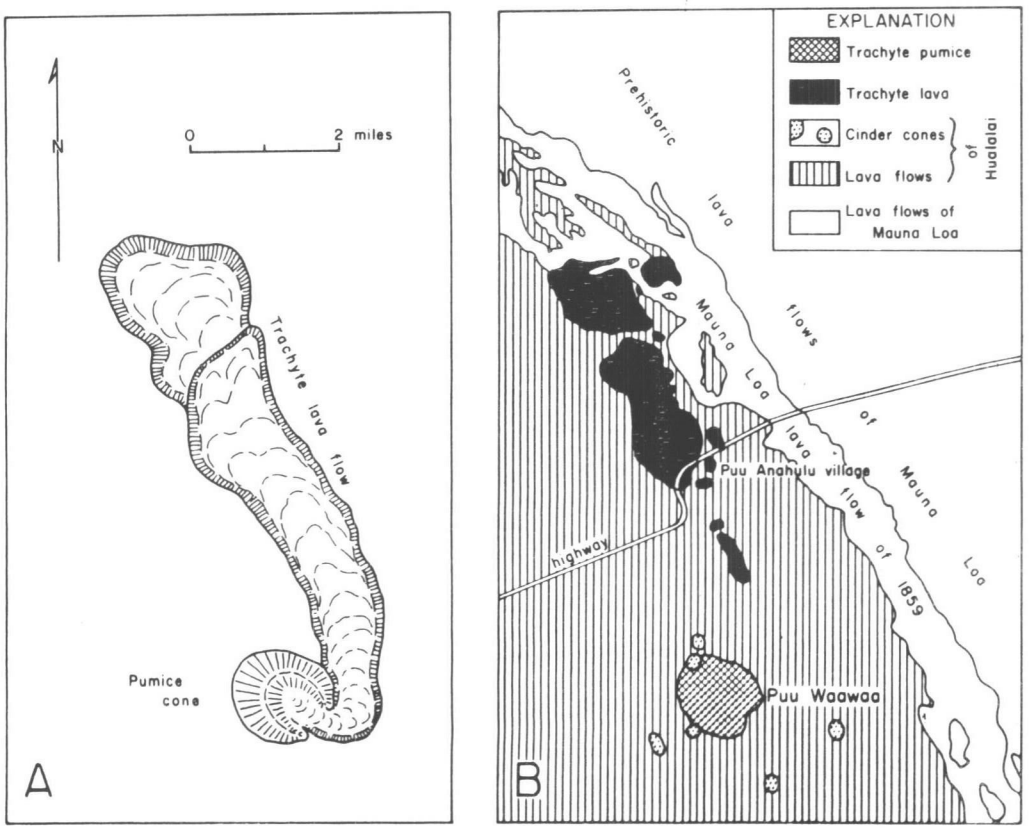


Figure 191. *A*, Diagram of the trachyte pumice cone of Puu Waawaa, on the northern slope of Hualalai Volcano, and the lava flow from it. *B*, Geologic map showing the relationship of the Puu Waawaa cone and flow to the later lava flows of Hualalai and Mauna Loa. (After Stearns and Macdonald, 1946.)

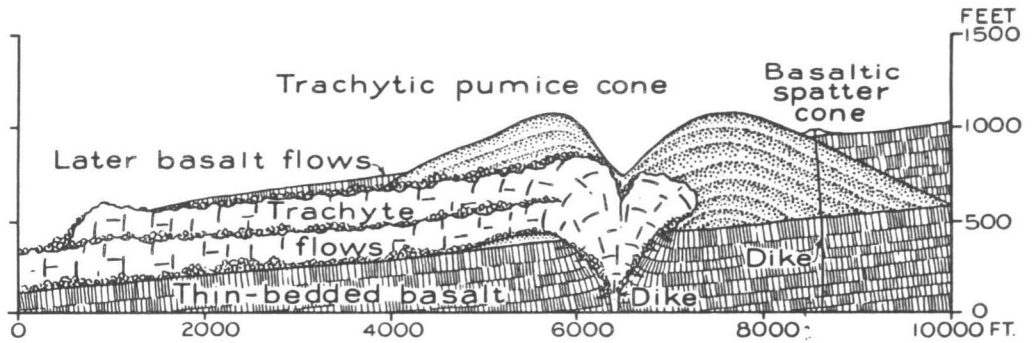


Figure 192. Diagrammatic cross section showing the relationship of the Puu Waawaa pumice cone and trachyte lava flow. (After Stearns and Macdonald, 1946.)

Mokuaweoweo caldera is 2.5 miles long and 1.5 miles wide (fig. 47). The cliff bounding it on the west is 600 feet high, but the one on the east is only 225 feet, and both decrease in height northward to only about 10 feet at the northeastern edge. At the south end the caldera merges with the adjacent pit crater known as South Pit (fig. 32), and during the 1949 eruption, lava flowed from the caldera into South Pit, filling it to overflowing. Two other pit craters, Lua Hohonu and Lua Hou, lie on the rift zone 0.3 and 0.7 mile southwest of South Pit.

Mokuaweoweo was first mapped by Lt. Charles Wilkes, the commander of the U.S. Exploring Expedition, in 1841. At that time it had a nearly circular central pit, 800 feet deep on the west side, bordered by crescentic benches on both the north and south. Still farther north the present North Bay was a separate pit crater. Since then eruptions in the caldera have gradually filled the central pit and overflowed the north and south "lunate platforms," extending the floor of the caldera across North Bay (fig. 47). Wilkes's map (fig. 47*A*) shows neither the East Bay nor Lua Poholo, and south of the caldera it shows only two pit craters instead of the present three: both East Bay and Lua Hohonu have been formed since 1841. (Lua Hohonu is now the one that should be named Lua Hou—"new pit.") Lua Poholo still did not exist when the area was mapped by J. M. Lydgate in 1874, but it had been formed by 1885, when Mokuaweoweo was again mapped by J. M. Alexander. The present condition of Mokuaweoweo is shown in figure 47*B*.

The Mauna Loa shield has been built principally by eruptions along two rift zones that extend southwestward and east-northeastward from the caldera (fig. 189). A less well defined rift zone, which fans out on the northern slope, gave vent to the great lava flow of 1859. Another, even less prominent alignment of vents extends northwestward down the western

slope of the mountain toward the summit of Hualalai. The rift zones are marked by scores of open cracks, an inch or two to 10 feet wide, along many of which spurting lava has built spatter ramparts from 1 to 20 feet high. Where the eruptions centralized in big lava fountains, the ramparts merge into cinder-and-spatter cones. Most of the cones are less than 100 feet high, but the lava cone of the 1940 eruption, in Mokuaweoweo, rises about 170 feet above its base, which is buried by flows from the same and later vents. More than 160 fissures and cones have been mapped on Mauna Loa.

The Halai Hills, in Hilo, are a row of three small cinder cones. They are covered with Pahala ash, and are correlated with the Kahuku Volcanic Series. The middle hill has been almost completely dug away for cinder used in the surfacing of secondary roads. It has been suggested that the Halai cones belong to Mauna Kea, but it appears more probable that they are early cones of Mauna Loa, since they are aligned parallel to the northeast rift zone of Mauna Loa and lie almost directly on the projection of that rift zone. Most of downtown Hilo lies on an ash-covered kipuka that has been sheltered from later lava flows by the Halai Hills.

Few eruptions have taken place along the lower 20 miles of the northeast rift zone during the time of formation of the Ka'u Series. However, one small spatter cone lies on the rift in the Waiakea Homesteads area, 4 miles southwest of Halai Hill. Spatter from this cone buried tree ferns and converted them into charcoal. Carbon-14 determinations on the charcoal show that the eruption occurred about 2,000 years ago.

Along the south shore of Hawaii, for about 14 miles west of South Point, a row of cinder and ash cones (fig. 178) has been built by littoral explosions where lava flows from the southwest rift of Mauna Loa entered the sea. The most recent of the cones (fig. 42) is an unusually large one, 240 feet high, known as Puu Hou (new hill), formed by the lava flow of 1868. Except in this area, only a few littoral cones are found around the shore of Mauna Loa. There are two on the Kona Coast, Puu Ohau and a small cone at Lae Auau, and 3 miles northeast of South Point, Puu Mahana is a littoral cone belonging to the Kahuku Series. Wave erosion has destroyed the seaward side of Puu Mahana, and grains of olivine from the cone have been concentrated in a small bay to form one of the best green sand beaches in Hawaii.

Near the coast the southwest rift zone is bounded along the eastern side by the north-south-trending Kahuku fault (fig. 189), along which the western side has been dropped down relative to the eastern side. The resulting fault scarp is 600 feet high at the coast. It can be traced inland some 10 miles, gradually decreasing in height until it disappears a short distance beyond the highway. Seaward, the scarp extends at least 18 miles beyond South Point. About 6 miles farther east the southeast-trending Waiohinu fault is displaced in the opposite direction. It extends 4.5 miles from Waiohinu to the sea, and has produced an eastward-facing scarp, generally less than 50 feet high. In 1868 lateral movement of several feet took place on the Waiohinu fault.

Along the southeastern base of Mauna Loa, the Kaoiki fault system (fig. 189) is a series of echelon tangential faults along which the mountainward side has moved relatively upward. Step faulting has produced a series of terraces separated by southeast-facing scarps that can be traced for 18 miles southwestward from Bird Park, near Kilauea caldera, to beyond Kapapala. The Kaoiki faults appear to provide a sort of expansion joint between Mauna Loa and Kilauea. When one or the other volcano is swelling or shrinking, adjustments take place in the form of movements on the faults, with resulting earthquakes. In places, the total height of the escarpment is more than 500 feet, but along part of its length the escarpment is veneered by later lava flows, and the visible height represents only part of the displacement on the faults, since its base is buried by later lava flows of both Mauna Loa and Kilauea. One of the flows is the very late prehistoric Keamoku flow, which originated from a vent at about 9,000 feet altitude on the northeast rift zone of Mauna Loa, flowed southeastward 10 miles down the flank of the mountain and over the Kaoiki fault scarp, then turned and flowed southwestward 5 miles along the base of the escarpment.

A series of older tangential faults extends southwestward from the Kaoiki escarpment to beyond Honuapo. They have been partly eroded and largely hidden by a cover of ash and later lavas, but near Honuapo the recent lavas have been offset a few feet by more recent fault movement.

Along the west slope of Mauna Loa, the escarpment at the northeastern edge of Kealakekua Bay (fig. 194) is the expression of the Kealakekua fault (figs. 157, 189). The damaging Kona earthquake of 1951 was caused by movement on this fault beneath the ocean, about a mile southwest of the tip of the peninsula north of the bay. A branch of the fault diverges northward and is responsible for the steep lava-mantled escarpment at the inland edge of the peninsula. Southeastward, the fault extends diagonally inland for about 3 miles beneath a cover of later lavas. Beyond there, it appears to bend southward, parallel to the coast, and to be responsible for the abnormal steepness of the lava-covered slope of that part of the mountain.

Farther south, the Kaholo Pali lies just inland from the shore for about 16 miles. This west-facing escarpment is almost entirely mantled by later lava flows. South of Hookena, the height of the escarpment is about 500 feet, but it decreases both northward and southward, and over most of its length it averages about 250 feet. There appears to be little question that the Kaholo Pali is primarily a buried fault scarp, although it may have been modified to some small extent by marine erosion.

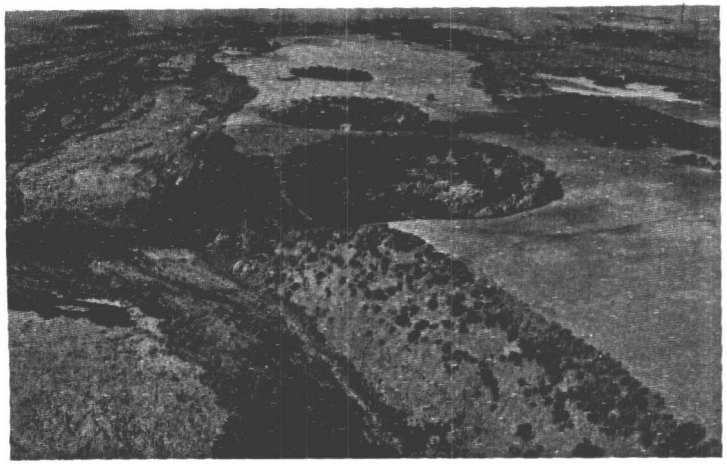


Figure 193. Three nearly circular pit craters lie along the crest of the Kahuku fault scarp 9 miles north of South Point, Hawaii. The closest crater is Lua Puali, the second is Lua Poai, and the third is unnamed. The fresh lava at the base of the scarp is part of the 1868 lava flow of Mauna Loa.

Figure 194. Kealakekua Bay, with Napoopoo in the foreground. The cliff on the right-hand side of the bay is a fault scarp. In the background, lava flows of Mauna Loa have poured over the cliff and spread out to form the Kaawaloa peninsula, on the near side of which Capt. James Cook was killed.

At many places near the shores of the island, the Ka'u Series is only a few flows thick. Kipukas of ash-covered Kahuku lavas are found southwest of Hilo, in addition to those already mentioned along the south slope near Pahala. Pahala ash is also encountered at shallow levels in water-development tunnels southwest of Hilo and near Pahala and Naalehu, where it perches ground water in the overlying Ka'u lavas. Ash which may be correlative with the Pahala ash is exposed in the cliff at the north side of Kealakekua Bay, overlain by 25 feet of Ka'u lavas. The rocks beneath the ash may belong to Hualalai, but more probably they are a part of the Kahuku Series.

In some of the kipukas on the south slope of Mauna Loa, such as that at South Point, the Pahala ash is as much as 40 feet thick, which is nearly the maximum thickness found on the remnants of the Ninole shield. These parts of the Kahuku Series must have remained unburied by lava flows through most of the time of accumulation of the Pahala ash. It is not now possible to tell whether the Mauna Loa shield remained inactive throughout this time, or whether its southeastern flank was shielded from lava flows by a high caldera wall and fault scarps paralleling the rift zone. More probably, however, activity shifted for a time almost wholly to the Kulani shield. That activity probably did not cease entirely at all vents is indicated by the fact that the ash on the eastern slope, between Keaau and Mountain View, although it totals about 15 feet in thickness, is shown by drill holes to be divided into several beds by intervening lava flows.

A low cliff, largely mantled with later lava flows, which extends for several miles northward from Kealakekua Bay, is probably a sea cliff. The lava flows beneath the later lava veneer are capped by a layer of ash 6 to 12 inches thick. The ash must have accumulated, and the sea cliff probably was cut, during a time when the Mauna Loa shield was inactive or when that part of the slope for some other reason received no lava flows.

Thus the evidence suggests that, at various intervals in its history, there were periods of at least several centuries during which lava flows did not reach some sectors of the volcano. Nevertheless, there is almost no sign of erosion between successive flows, probably because of the high permeability of the lava surface which allows water to sink in instead of running off. Only one noteworthy exception is known. Above Hilo, the Wailuku River has been crowded northward against the slope of Mauna Kea by successive lava flows of Mauna Loa, and it now follows approximately the boundary between the two volcanoes. Despite loss of water into the Mauna Loa lavas, the river is kept flowing by many tributaries that enter it from the ash-covered slopes of Mauna Kea. At some time within the last few millenia, the river was able to cut a shallow gorge, seldom more than 50 feet deep, along the edge of the Mauna Loa lavas. Still later, the gorge was refilled by another lava flow, which in turn is now being eroded. A cross section of the flow can be seen at Rainbow Falls, in Hilo, where at the north edge of the plunge pool the old valley floor can be seen sloping southward, overlain by the later lava. Along the south side of the plunge pool, springs issue at the bottom of the lava flow. The water for the springs is derived by leakage from the river farther upstream. Chilling of the lava against the valley side caused columnar jointing, which can be seen in the face of the fall. The cross sections of columnar joint columns are well exposed also at the Boiling Pots—a series of potholes cut by the river about a mile upstream from Rainbow Falls. Through most of its lower course the Wailuku River follows the former feeding channel of the late lava flow. Maui's Canoe is a remnant of the flow downstream from the falls.

KILAUEA

The rocks of Kilauea are divided into the older Hilina Volcanic Series and the younger Puna Volcanic Series (fig. 178). The Hilina Series is capped by Pahala ash, and is believed to be coeval with the Kahuku Series on Mauna Loa. The Puna Series overlies the Pahala ash and is correlative with the Ka'u Series of Mauna Loa. Lava flows of the Puna and Ka'u series interfinger along the boundary between the two volcanoes. Both the Hilina and the Puna series consist of pahoehoe and aa lava flows of tholeiitic basalt, olivine basalt, and oceanite, and associated cinder-and-spatter cones and ash deposits.

The Hilina Series is exposed only in fault scarps along the southern coast. In the Hilina Pali a succession of about 1,000 feet of thin lava flows is exposed. A few thin beds of vitric tuff lie between the flows. A similar section is exposed in the seaward face of Puu Kapukapu.

The Pahala ash is 30 feet thick in Hilina Pali and 40 feet thick on Puu Kapukapu (fig. 179). Most of it is sandy to silty yellow vitric ash, resembling most of the outcrops on Mauna Loa, but in Hilina Pali coarser beds containing pumiceous lapilli and Pele's tears are abundant. They must have been derived from vents relatively close by, probably not farther away than Kilauea caldera. As on Mauna Loa, the thick deposits of Pahala ash in the Hilina Pali area mark an interval during which no lava flows reached that part of the volcano. However, the coarse lapilli at Hilina Pali, as well as the great thickening of the ash in the Pahala region, indicate that Kilauea volcano was active during this interval. The Hilina Pali area was probably protected from lava flows by north-facing cliffs formed by collapse around the caldera and along the adjacent rift zones.

The lavas of the Puna Volcanic Series were erupted almost entirely from vents in the area of the present Kilauea caldera and along two rift zones that extend eastward and southwestward from the summit of the volcano (fig. 189). At the top of the Hilina fault scarp they are only one or two flows thick, but in the cliff at the western side of the caldera lava flows totaling about 420 feet thick are exposed.

Before 1919 a thick bed of yellow ash (the Uwekahuna ash) was exposed at the base of the cliff, and if it is the same as the similar Pahala ash the total thickness of the Ka'u lavas at that place is only a little more than the thickness now visible in the cliff. Elsewhere their base is not exposed, and their thickness is unknown.

Kilauea caldera consists of a central, well-defined, oval sunken area 3 miles long, 2 miles wide, and a little more than 400 feet deep at its western edge, surrounded by a series of benches which have not sunk as much (figs. 57, 195). The inner caldera is bounded throughout most of its circumference by abrupt fault scarps. In two places, however, the collapse has been in the form of step faulting. The step-fault blocks beneath the Volcano House, at the northeastern edge of the caldera, are irregular, and a graben 50 feet deep lies behind one of the blocks. Those at Uwekahuna, on the west side of the caldera, are quite regular. Near the southern edge of the caldera a horst (the "Sand Spit") projects from the eastern wall. The southeastern wall is low and banked with ash from eruptions within the caldera. In 1921 a short lava flow escaped through a low gap in the southeastern wall of the caldera (fig. 195). With the exception of the Sand Spit, the entire inner caldera floor is covered with lava erupted within the last century. Halemaumau, in the southwestern part of the caldera floor, is a collapse crater that occupies the top of a very flat cone or shield which slopes off in all directions to the edge of the caldera floor. Through the last 150 years Halemaumau has been the main focus of surface activity of Kilauea.

Surrounding the central caldera is a series of benches. For the most part they also are bounded by well-defined fault scarps, but in some places the faults pass into sharp monoclinal down-bends of the surficial lavas. Individual faults tend to die out and be replaced by others arranged en echelon (fig. 195). Particularly on the southwest side, the marginal area gives the impression of having sagged toward the inner caldera. The diameters of the outer sunken area are approximately 3 by 4 miles.

On the southwest the caldera merges with the rift zone, which is there bounded on the south by a series of faults trending parallel to it and down-thrown on the north side (fig. 195). Another series of less conspicuous faults extends southwestward from the caldera along the north side of the rift zone, which thus lies within a shallow graben. Farther southwest the fault scarps along the south side, if they ever existed, have been buried by lava flows; but a series of south-facing fault scarps lies along the north edge parallel to the nearby Kaoiki fault system on Mauna Loa.

The east rift zone of Kilauea extends east-northeastward, from the faults bounding the south edge of the southwest rift zone, 28 miles to Cape Kumukahi, and at least 70 miles farther beneath the ocean. It is linked to the caldera by a row of seven pit craters that trends southeastward to Pauahi Crater (fig. 62). This line of pit craters is crossed almost at right angles by both the outer boundary faults of the caldera and the faults bounding the southwest rift zone, and it is noteworthy that the eruptive fissure of the 1962 eruption, near Aloi Crater, was parallel to these faults, not to the line of pit craters. Between 1938 and 1942, horizontal movement on these faults offset the Chain of Craters Road about 4 feet, the northern side of the fault moving eastward. Similar movements occurred again during the 1962 and 1963 eruptions, again with the north side moving eastward on several faults for an aggregate displacement of several feet. This was accompanied by vertical movement on one fault, with the north side moving upward nearly 3 feet.

In the 7 miles east of Pauahi Crater six other pit craters lie along the rift zone (figs. 62, 77). Beyond that point, however, there are no others for 16 miles to the east. This region of numerous pit craters must mark a zone of large intrusions from the central magma body of the volcano that have approached close to the surface.

Two small pit craters on the southwest rift zone, 3 miles from the caldera, lie above a large lava tube and were probably formed by collapse of the roof of the tube. Puulena, Pawai, and Kahuwai craters, on the east rift zone 7 miles southwest of Cape Kumukahi, are small pit craters perforating the summits of small lava shields.

Lava beds in the walls of Kilauea caldera slope away from the caldera and project into the air where the caldera is now located. This indicates that the caldera must once have been much smaller, or perhaps it did not exist at all. The summit of the Kilauea shield was complex, consisting of several coalescing smaller shields. One occupied the position of the present caldera. Another is still clearly discernible on the east edge of the caldera. Its summit collapsed to form Kilauea Iki Crater. Another small shield on the side of the Kilauea Iki shield is indented by the two small Twin Craters, one of which was drained by the Thurston Lava Tube.

Other small parasitic shields lie on the rift zones. Kane Nui o Hamo and Heiheiahulu, on the east rift zone (figs. 62, 68), and Mauna Iki, formed by the 1920 eruption on the southwest rift zone, are examples. However, most of the discrete cones on the rift zones are spatter or spatter-and-cinder cones. Among the largest of these are the Kamakaia Hills, 100 feet high, on the southwest rift (fig. 58), and Kalalua and Iilewa craters on the east rift (figs. 68, 76). Kapoho Cone, 2 miles inland from Cape Kumukahi (fig. 74), is a tuff cone formed by a phreatomagmatic eruption. The cone of the 1960 eruption, just north of the Kapoho Cone, also consists in large part of ash formed by phreatomagmatic explosions. The basal ground water lies only about 80 feet below the surface in this area. Phreatic explosions have thrown out small amounts of lithic ash and blocks around Aloi Crater, Puulena, and Pawai Crater. Near the rim of Puulena Crater some of the blocks weigh several tons. The phreatic explo-

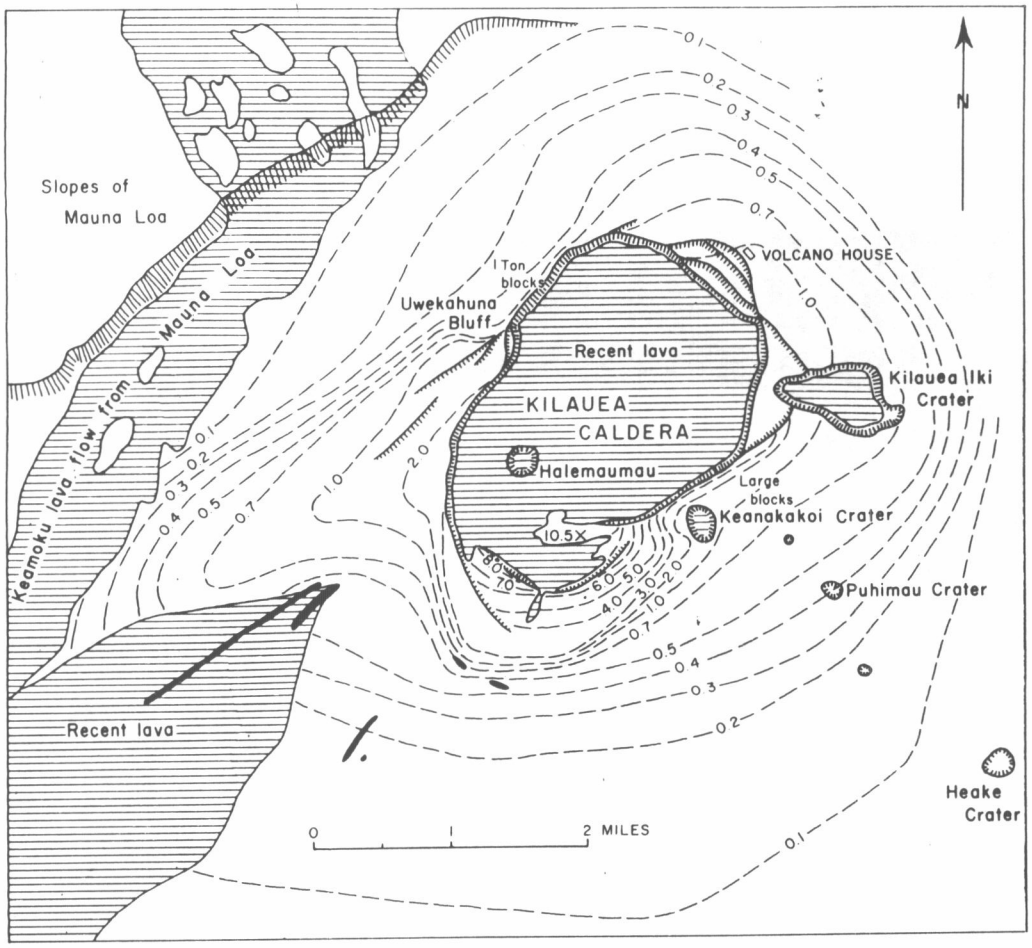


Figure 196. Map showing thickness of surficial ash deposits around Kilauea caldera. The dashed lines are isopachs (lines of equal thickness) indicating the depth of the ash cover, in meters. (After Stearns and Clark, 1930.)

Kapukapu fault and a fault of smaller, opposite displacement lying about half a mile inland. The low ridge seaward of Kalapana village also is a horst, and the village lies within a graben. Movement has continued on the Hilina fault system until recent times. Along the foot of the escarpment west of Kalapana the veneer of recent lavas is broken by a scarplet 10 feet high. During the violent earthquakes of 1868 the floor of the Kalapana graben subsided several feet, allowing ocean water to invade the old churchyard.

The southern slope of the east rift zone east of the Kalapana-Pahoa road undoubtedly owes its abnormal steepness to fault scarps that have been buried by later lava flows. Similar steep slopes are found in the ocean floor both south of the island and along the southern slope of the rift-zone ridge east of the island; they are almost certainly the result of submarine faulting.

A broad submarine ridge south of the island of Hawaii (fig. 199) has been interpreted by Moore (1964) as a huge landslide block that has moved outward and downward from the southern flank of Kilauea volcano, leaving the Hilina and associated fault scarps as part of the scar at the head of the slide. Alternatively, Macdonald (1955) interpreted the mass as another shield volcano built against the southern slope of Kilauea in the same way that Kilauea lies against the slope of Mauna Loa. The crest of the supposed submarine shield lies on the prolongation of the principal rift zone of Hualalai and the minor northwestern rift that crosses the western slope of Mauna Loa. At present, neither hypothesis for the origin of the submarine mass can be proved.

sions that took place at Halemaumau in 1924 have already been described (page 77). The area around Halemaumau is heavily covered with blocks and ash from that eruption.

In the immediate vicinity of the caldera, the surface of the lava flows is mantled with a deposit of ash. On the Sand Spit, within the caldera, the ash is more than 30 feet thick, and along much of the southwestern rim of the caldera, more than 10 feet. The deposit thins in all directions away from the caldera (fig. 196). It is well exposed in the fault scarp along the east side of the caldera south of Keanakakoi Crater, in road cuts and cracks around the south side of the caldera, and in cuts along the Mamalahoa Highway north of the caldera. Near the caldera the lower several inches of the deposit generally consists of pumice (reticulite) similar to that formed in abundance during the Kilauea Iki eruption of 1959. In many places the pumice rests on a layer of red ashy soil, which suggests that, for a considerable period, weathering of the surface of this part of the volcano was not interrupted by volcanic activity—a period of quiescence of at least this part of Kilauea that may have lasted several hundred years. Above the pumice layer, most of the deposit consists of vitric ash with occasional pumice lapilli, derived from the spray of lava fountains; but occasional layers of lithic ash and lapilli were formed by phreatic explosions. Along the southwest edge of the caldera the lithic ash of the 1924 explosions forms a layer a few inches thick, overlain only by scattered pumice of later eruptions. The 1924 ash is separated by several inches of vitric ash from the lithic debris of the 1790 eruption. Especially in the area near Keanakakoi Crater, the lower part of the 1790 deposit contains many cored bombs and lapilli with shells of magmatic material, indicating that magma was involved at least during the beginning of the eruption. Coarse pumice overlying the 1790 ash came from big lava fountains during the return of activity following the 1790 collapse.

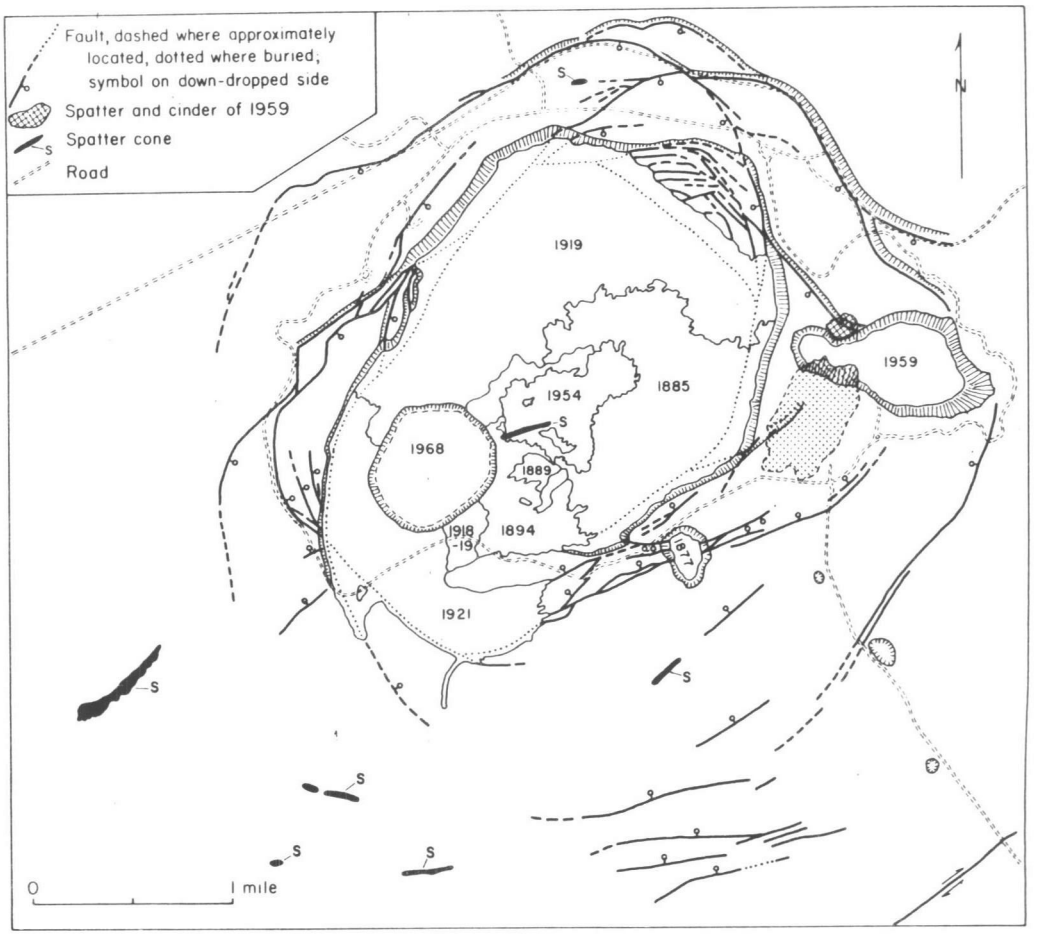


Figure 195. Map of Kilauea caldera and surroundings, showing the distribution of faults bounding the sunken area of the caldera, and the dates of some historic lava flows on the caldera floor. The more prominent fault scarps are shown by hachures. (Modified after Peterson, 1967.)

The tangential faults of the Hilina fault system lie along the southern slope of Kilauea. The system consists of a series of subparallel and en echelon faults (fig. 197) with a total downthrow on the seaward side of more than 2,000 feet. The Hilina Pali has a maximum height of 1,500 feet. Westward it becomes lower and then disappears beneath recent lava flows from the southwest rift zone. To the east it merges with the Poliokeawe Pali, which decreases in height eastward and disappears about 4 miles west of Kalapana. Throughout most of its length the Hilina-Poliokeawe escarpment is mantled with late lava flows (fig. 198), but lavas of the Hilina Series are exposed in windows. The seaward face of Puu Kapukapu is a fault scarp more than 1,000 feet high, plunging directly into the ocean. Puu Kapukapu is a small horst lying between the main

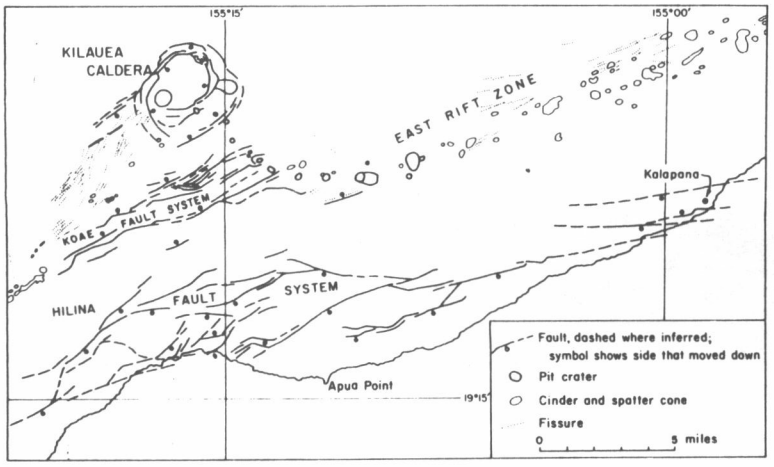


Figure 197. Map showing the pattern of faults in the Hilina fault system, on the southern flank of Kilauea volcano. (Modified after Stearns and Macdonald, 1946.)

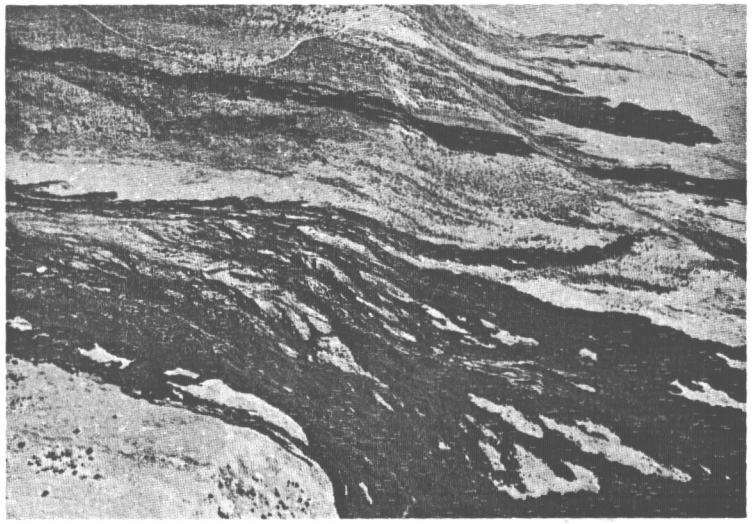
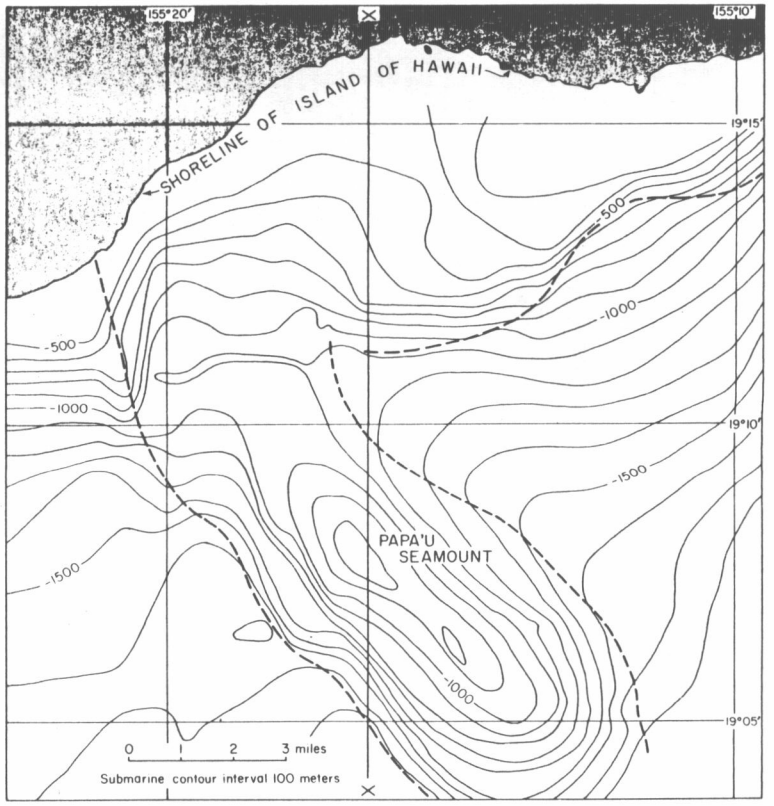


Figure 198. View eastward along Poliokeawe, one of the fault scarps of the Hilina system on the south slope of Kilauea. Converging with it from the right is another of the fault scarps, the Holei Pali. The black lava flows in the foreground, between the camera and the Kalapana road, were formed in 1969. Other older flows can be seen mantling the scarp.



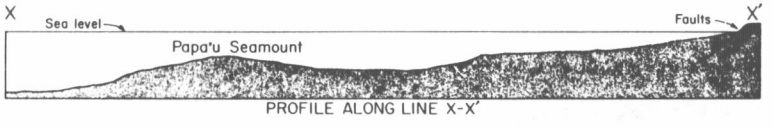


Figure 199. Map and profile of Papa'u Seamount, just south of the southern coastline of Kilauea volcano. (After Moore and Peck, 1965.) Moore and Peck consider the areas bounded by the heavy dashed lines to be huge landslides that have slid southward from the flank of Kilauea volcano; but it appears more probable that Papa'u Seamount is a shield volcano built along a rift zone with the same trend as that of Hualalai, with its flanks modified by faulting.

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7. AERIAL RECONNAISSANCE OVER THE ISLAND OF HAWAII

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By necessity, most planetologists use photogeological techniques in their interpretation of planetary surfaces – interpretations that include geological mapping, analysis of specific surface features, and determination of geological processes. It is fitting, therefore, that planetologists make aerial observations of terrains that may be analogous to planetary surfaces and to relate their observations to field studies conducted on the ground. Hopefully, this learning process will lead to a more complete understanding of the origin, structure, morphology, and subsequent degradation of various geological features, which, in turn, will result in better interpretations of planetary surfaces.

Hawaii is particularly spectacular from the air (weather permitting!), especially in terms of geology. Many volcanic features are so large that it is only from the air that their true perspective can be gained. This is particularly true of the larger shield volcanoes, lava tubes and channels, and complex multiple lava flows and flow units.

This aerial reconnaissance has been planned to show the maximum volcanic morphology in the time permitted and to cover most of the same regions as the field trips on the ground. Figure 7-1 shows the general flight path, which is divided into 15 segments. Each segment of terrain along the flight is shown with an air photo mosaic and corresponding topographic map. The air photo mosaics were taken from Soil Conservation Service quadrangle mosaics, prepared from aerial photographs taken in the 1950s (thus, the younger lava flows are not shown). The topographic maps are segments of 15′ quadrangles made mostly in the 1920s, which were only *slightly* updated here to include the more prominent recent features.

The flight sequence in this guide is *nominal* and based on optimum weather conditions; it may be altered, depending upon weather and visibility. Also included at the end of the flight sequence for the island of Hawaii are sections for parts of Maui (Haleakala Volcano) and Molokai, which will be flown if Hawaii is completely obscured at flight time.

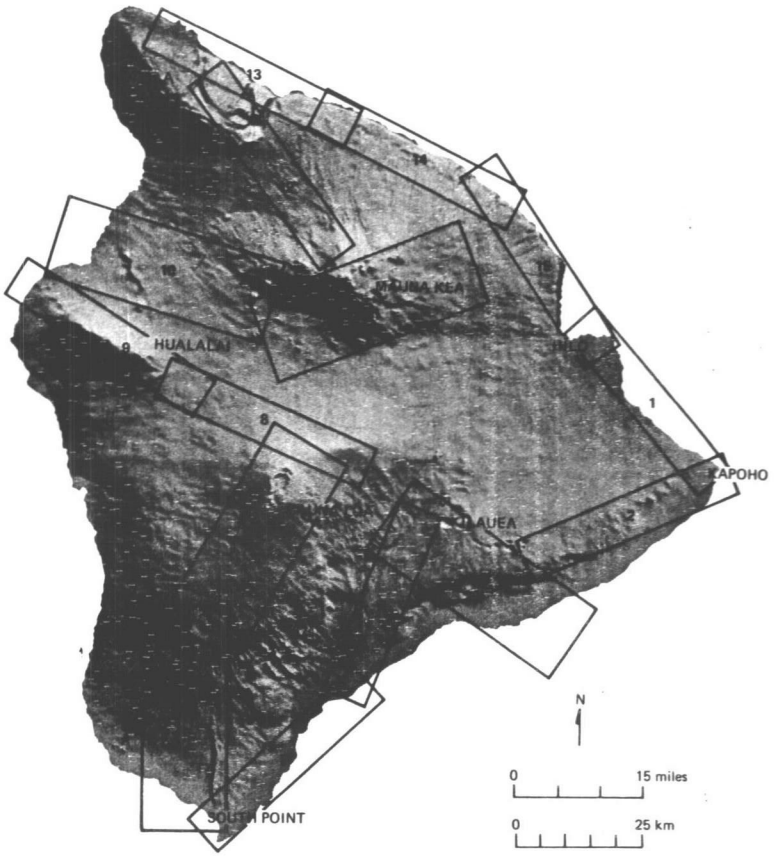

Fig. 7-1. Index to mosaics and maps along flight path over island of Hawaii.

Photographs, particularly color transparencies, will provide a good supplement to the guide, especially if they are keyed to the various segments of the flight path. To offset vibration and ground motion, a shutter speed of at least 1/250 sec is recommended. Although Kodachrome II is entirely adequate under bright light, the possibility of clouds suggests faster film, such as High Speed Ektachrome.

Lighting conditions for aerial photography are tricky at best and are even more difficult over dark basalt flows. For cameras with built-in light meters, be certain that the meter is "seeing" the desired subject. Pictures are often underexposed because the meter measured mostly the sky. To get the proper exposure for dark lava flows, tip the camera (or the light meter) so that it "sees" only the ground and no sky. The picture can be composed after the proper light reading is obtained. For particularly interesting features, it is a good idea to "bracket" the exposure, using one "f" stop above and one "f" stop below the nominal value. The price of film is the least expensive part of the trip!

A haze, or UV filter, is also recommended. If a polarizing filter is used, watch for refraction produced by the polarizing effect of the airplane window. In addition, bring a soft cloth or tissue to wipe the window. Extra film is a good investment. Invariably, film runs out before the flight is over. If you are prone to motion sickness, your colleagues would appreciate your taking Dramamine (or something similar) *prior* to the flight (generally it doesn't do much good to take the medication after you begin to feel queasy). The dips, turns, and banks of the reconnaissance flight can bring problems even to the staunchest flier.

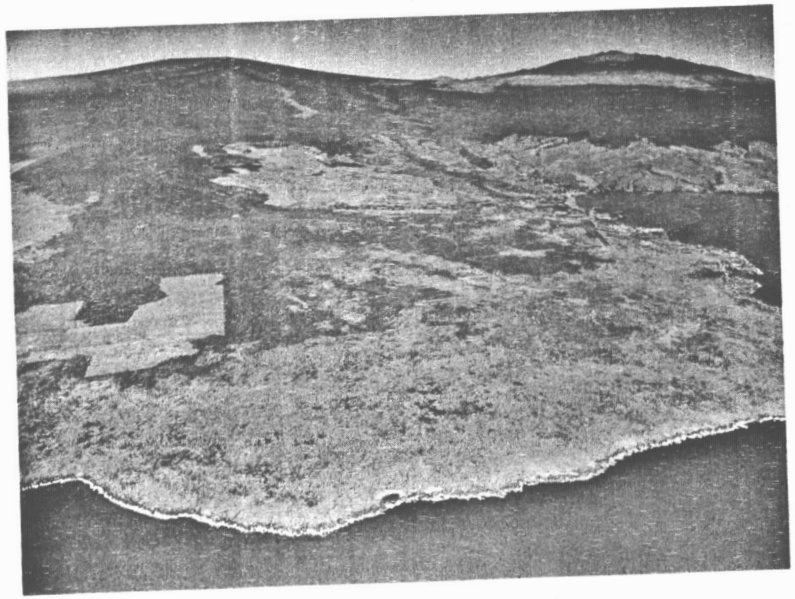

Fig. 7-2. View westward toward Hilo Bay and Hilo (right of center), across the Hilo Lava Plain (Abbott, 1973). Note the contrast between the smoothly rounded profile of Mauna Loa (left), built predominently by flows, with the steeper slopes of Mauna Kea (right), topped in part by pyroclastic deposits. Summit of Hualalai shield volcano is barely visible in the saddle on the horizon. (*U.S. Navy photograph, 1954.*)

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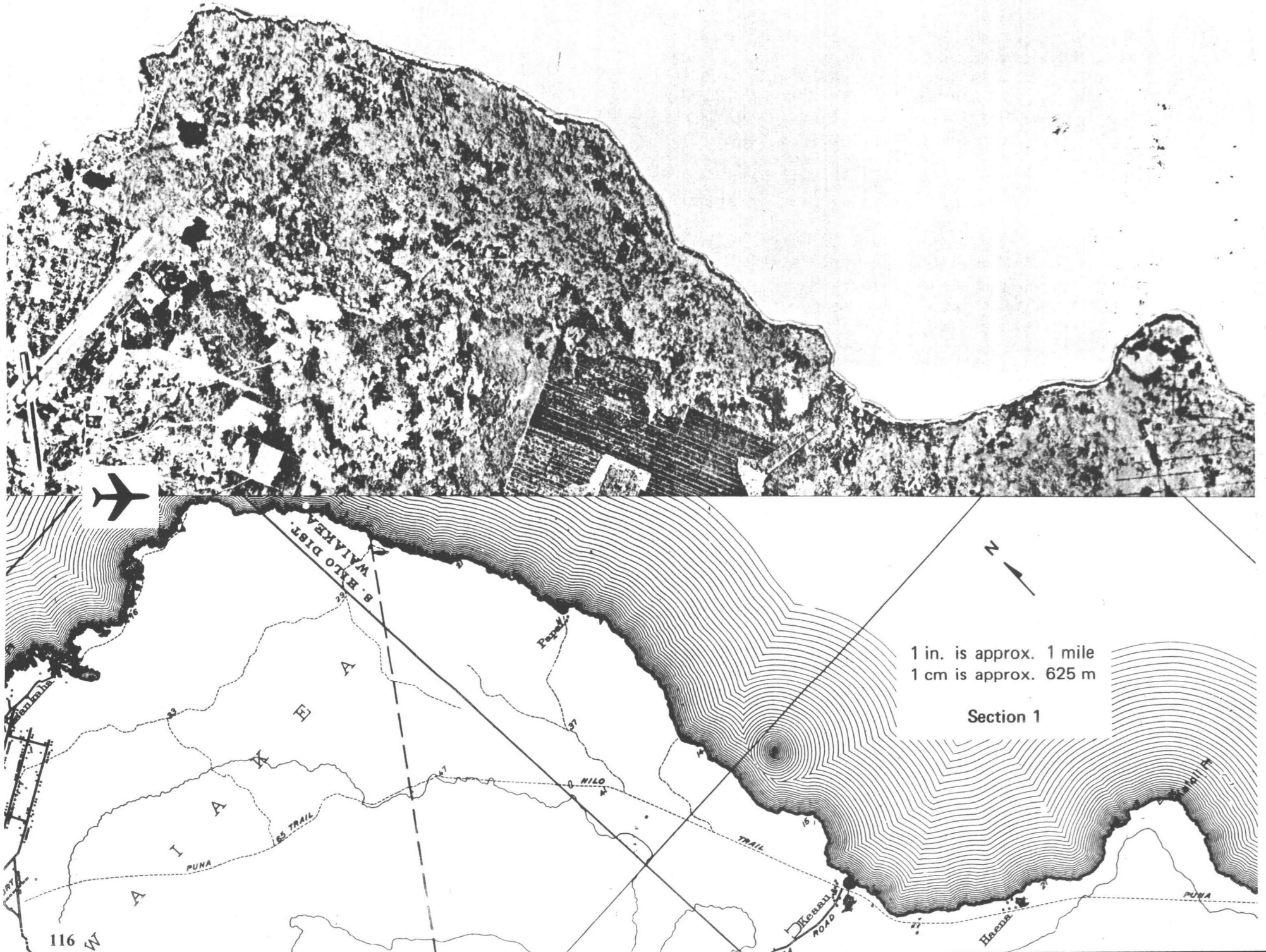
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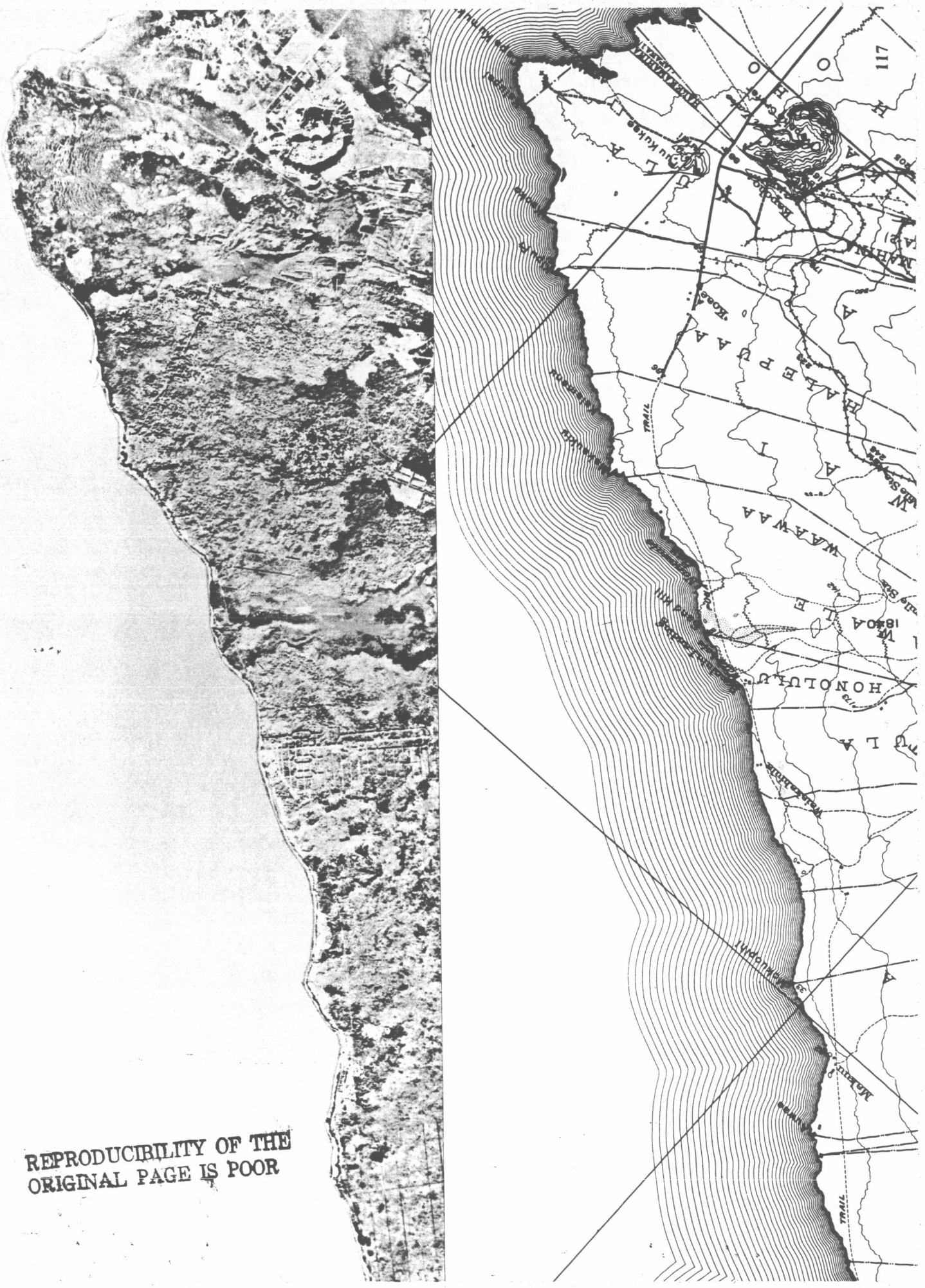
PUNA
NILO
TRAIL
ROAD
PUNA



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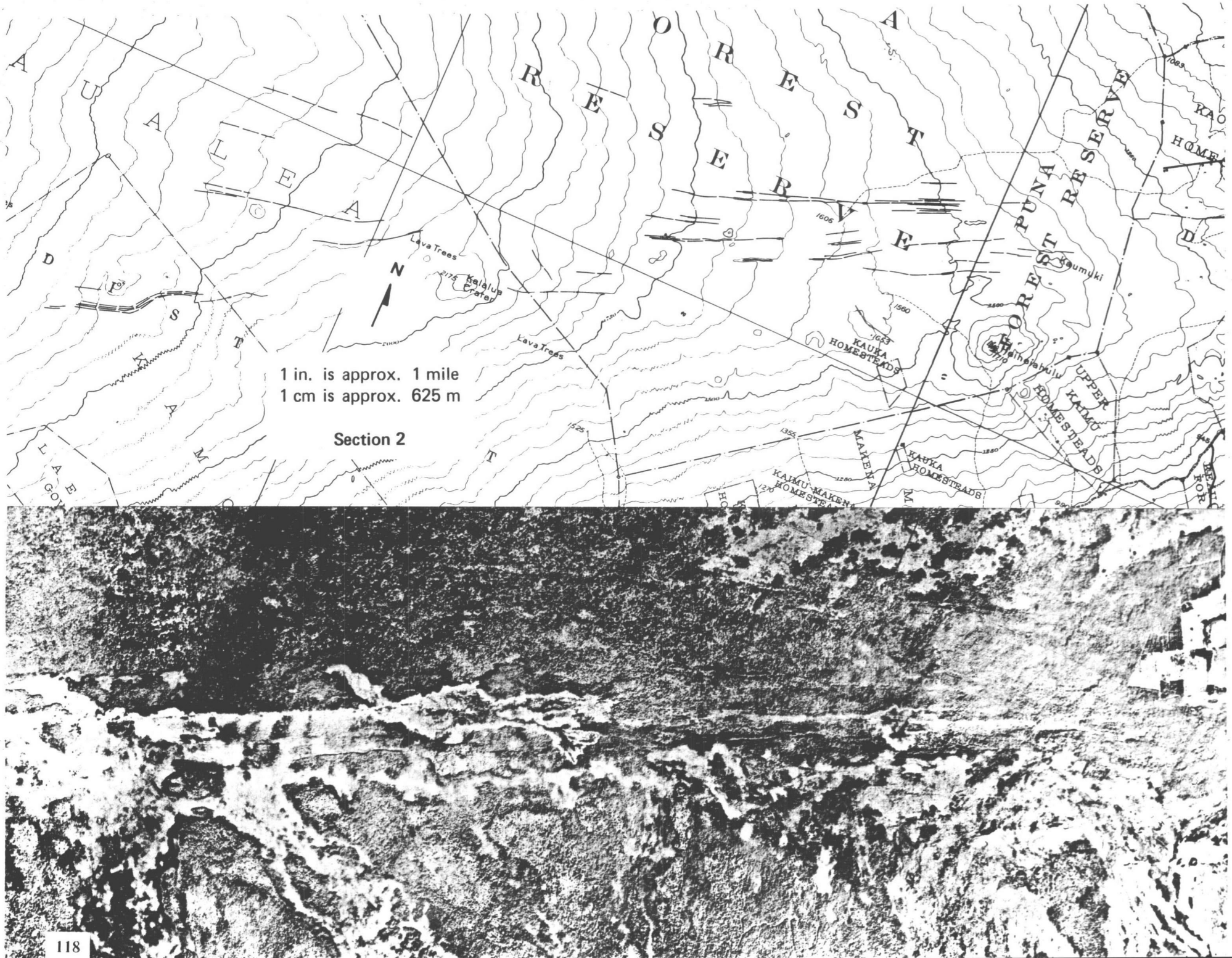
AUAUEA
FOREST RESERVE
PUNA FOREST RESERVE
Lava Trees
Kalalua Crater
Lava Trees
KAUKA HOMESTEADS
UPPER KAIMU HOMESTEADS
KAIMU-MAKENA HOMESTEADS
KAUKA HOMESTEADS
MAKENA
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Section 2

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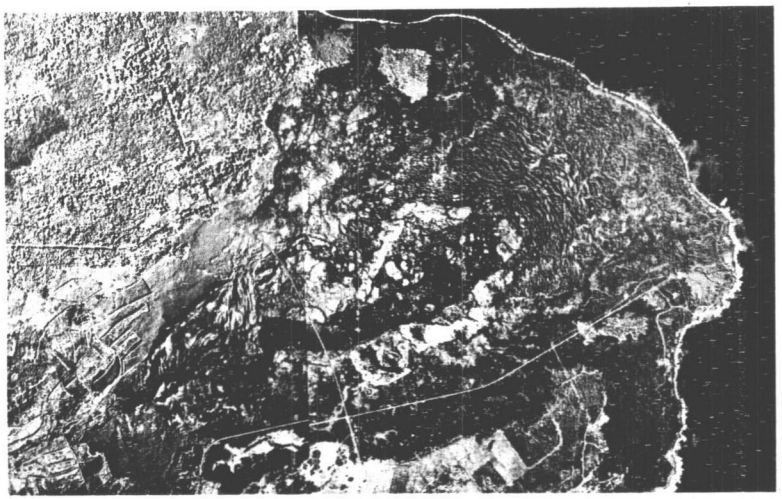

Fig. 7-3. Vertical aerial photograph mosaic of the Kapoho area showing the extent of the primary flows from the 1960 eruption on the east rift zone, Kilauea Volcano (north is to the top). (*U.S. Dept. of Agriculture photograph, EKL, 1965.*)

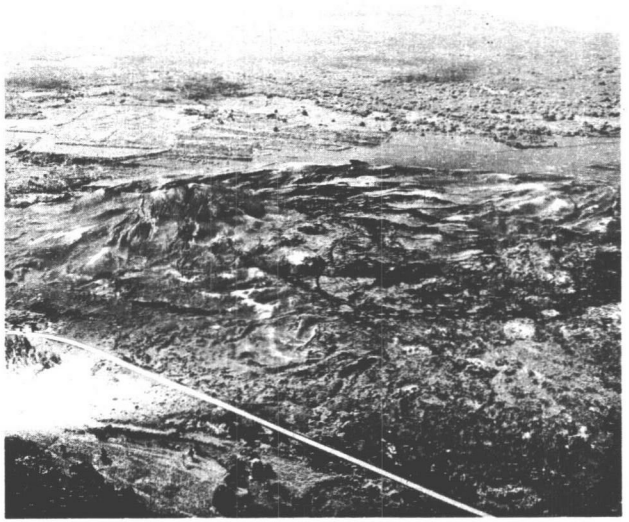

Fig. 7-4. Oblique aerial view of Puu Laimana, one of the tephra cones formed during the 1960 eruptions at Kapoho, showing extensive slumping of the fragmental deposits making up the cone. (*U.S. Air Force photograph, 1966; contributed by the Hawaiian Volcano Observatory.*)

Fig. 7-5. View southeastward across tephra cone: Puu Laimana and Kapoho Crater (middle). (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

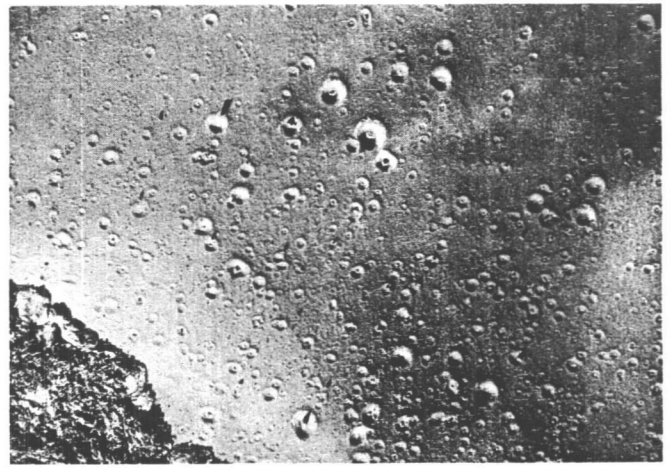

Fig. 7-6. Meter-scale secondary impact craters formed by volcanic ejecta during the 1960 eruptions at Kapoho (Hartmann, 1967). (*Photograph by L. Nichols, 1965, contributed by William Hartmann, Planetary Science Institute Associates, Tuscon, Arizona.*)

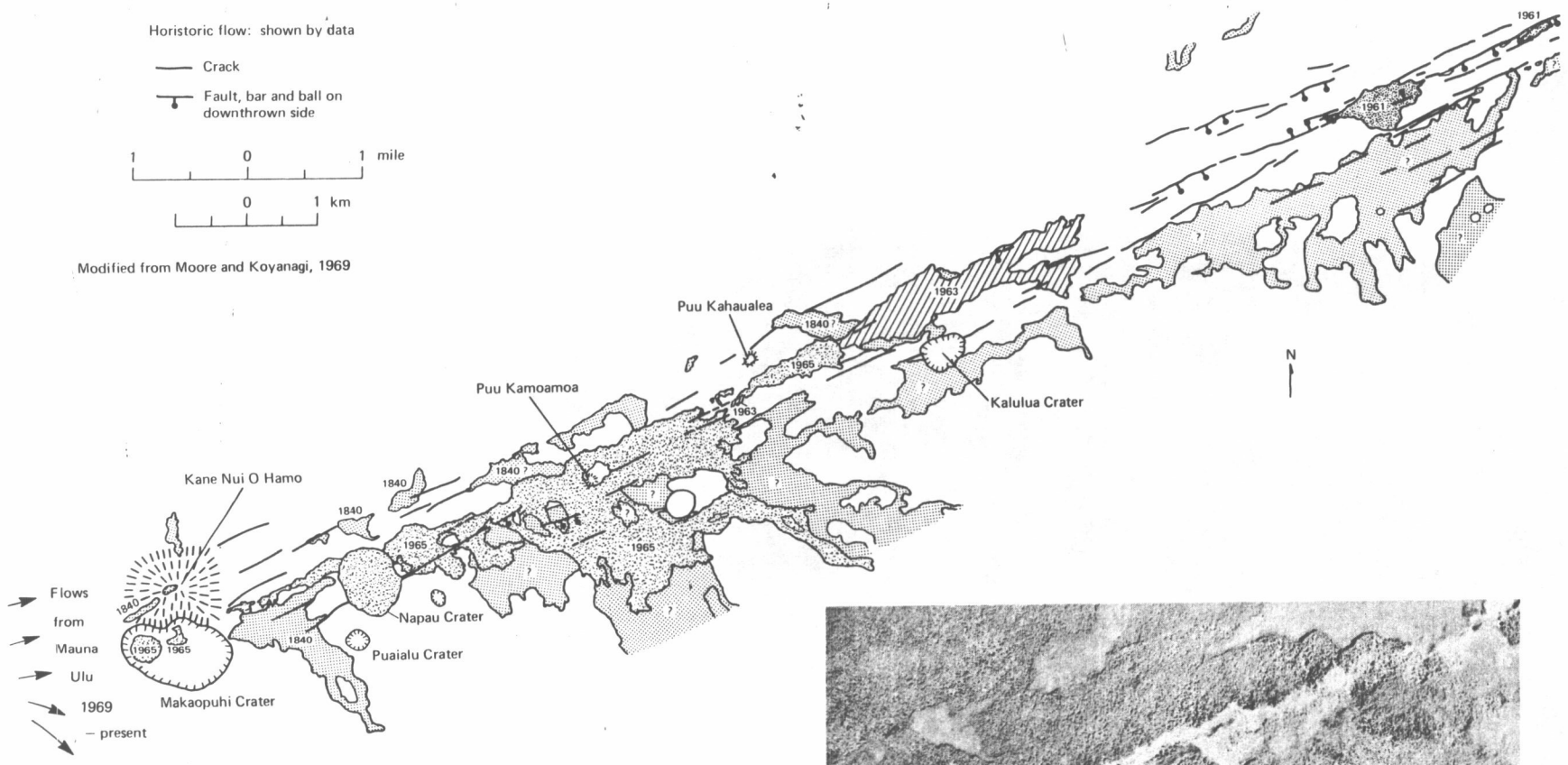

Fig. 7-7. Geologic map of the central part of the east rift zone of Kilauea Volcano showing the main historic lava flows (after Moore and Koyanagi, 1969).

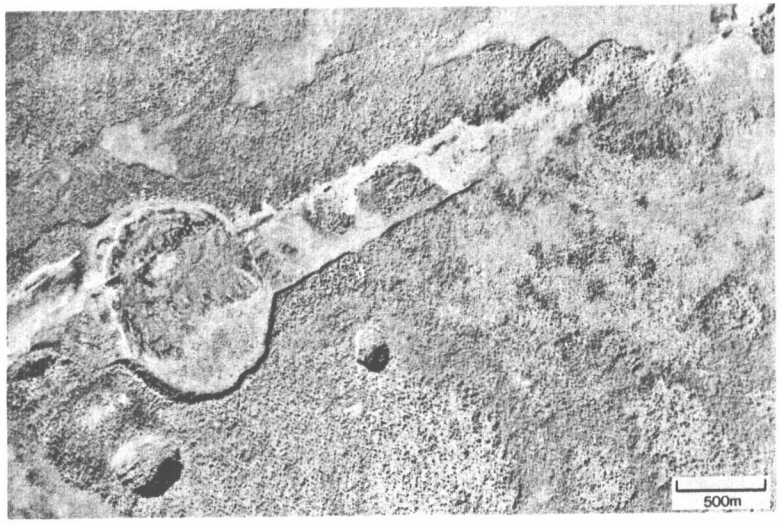

Fig. 7-8. Vertical aerial photograph of Napau Crater on the east rift zone of Kilauea. The crater has been transected by faults and fissures of the rift zone. Since the photograph was taken, the area has been modified by subsequent lava flows. (*U.S. Dept. of Agriculture photograph, EKL-12CC-143, 1965.*)

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1 in. is approx. 1 mile
1 cm is approx. 625 m

Section 3

HAWAII VOLCANOES NATIONAL PARK
KILAUEA
KILAUEA FOREST RESERVE
KILAUEA IKI
HALEMAUMAU
KILAUEA CRATER
KILAUEA MILITARY CAMP
KILAUEA IKI TRAIL
CRATER RIM DRIVE
CHAIN OF CRATERS ROAD
HALEMAUMAU TRAIL
KAU DESERT TRAIL
KAU FOREST RESERVE
KAU DESERT
PUU ULAULA
PUU KOAE
PUU HOKUKANO
PUU PUAI
PUU HOLUA
PUU KAMAKAU
PUU KAPUKAPU
PUU KAMOKU
PUU KAMOKU LAVA FLOW
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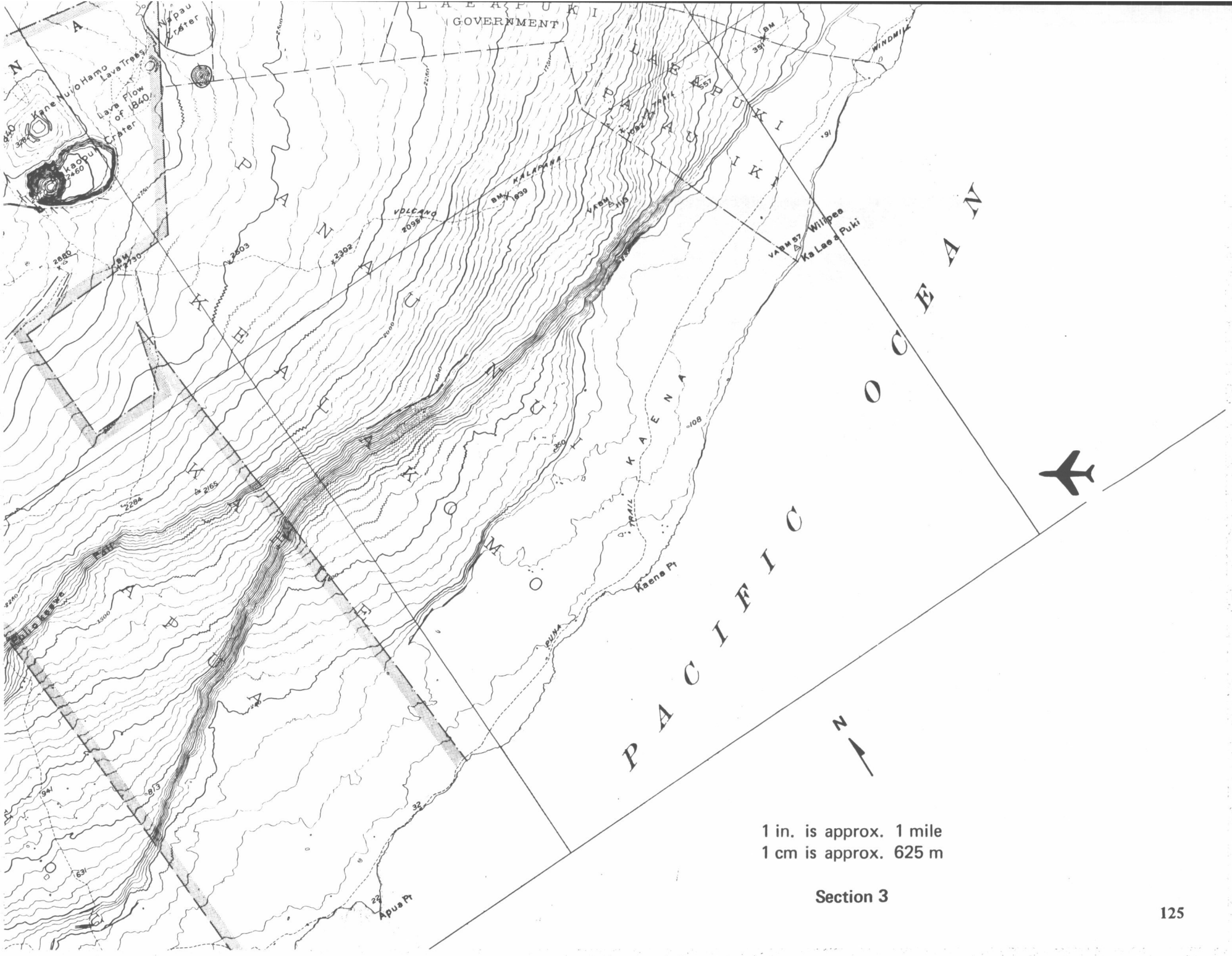
GOVERNMENT
Napau Crater
Kane Nui o Hamo
Lava Trees
Lava Flow of 1840
Puu Kao
Crater
Volcano
Kalanaina
Wilipee
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Apua Pt
PACIFIC OCEAN
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Section 3

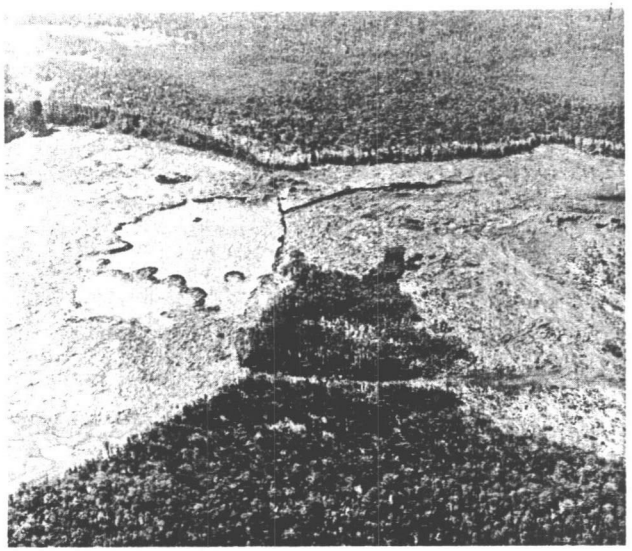


Fig. 7-9. View of the east rim of Napau Crater showing partly drained, perched lava lake (left-center) and faults of the east rift zone of Kilauea, trending eastward from the crater rim. (*NASA-Ames photograph by Mike Lovas, 1970.*)

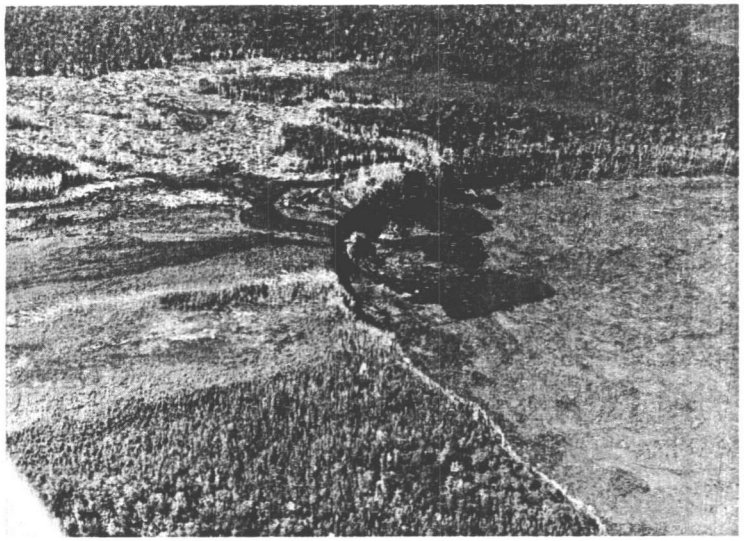


Fig. 7-10. View northward across the west rim of Napau Crater and the 1969 flows that poured over the rim, forming "lava fans." (*NASA-Ames photograph by Ronald Greeley, 1970.*)

Fig. 7-11. View west southwestward toward Mauna Ulu (rising fume, right-center) during early stages of its formation in 1969. Makaopuhi Crater is on the left. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

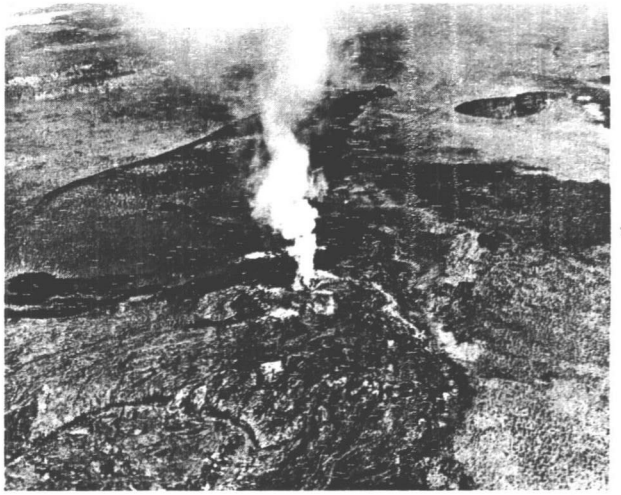


Fig. 7-12. View southwestward across Mauna Ulu (marked by rising fume) during eruptions in 1970. Alae Crater, lower left, had been nearly buried by flows (and has been subsequently buried). Chain of Craters Road trends diagonally from the upper right and is terminated by flows. Puu Huluhulu, a spatter cone, is to the right of Mauna Ulu. Prominent crater in right background is pauahi. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

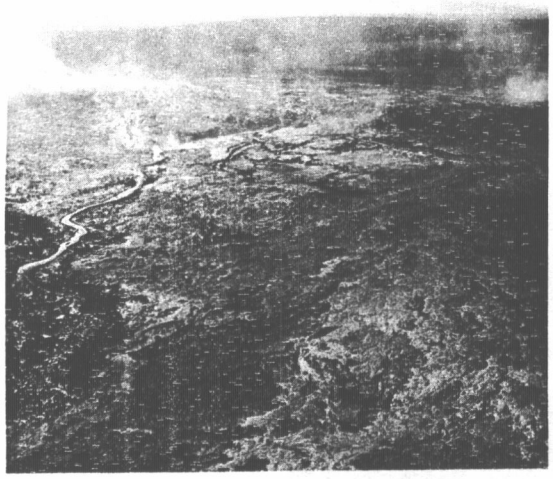


Fig. 7-13. View northward toward Mauna Ulu (fume on the left marks the vent area). Note the active lava flow channel that feeds the flow front on the left. Scarp-bound oval at right-center is the subsided crust of a lava lake which filled Alae Crater. The subsidence resulted from drainage of the lake via lava tubes (*NASA-Ames photograph by Ronald Greeley, August 1970.*)

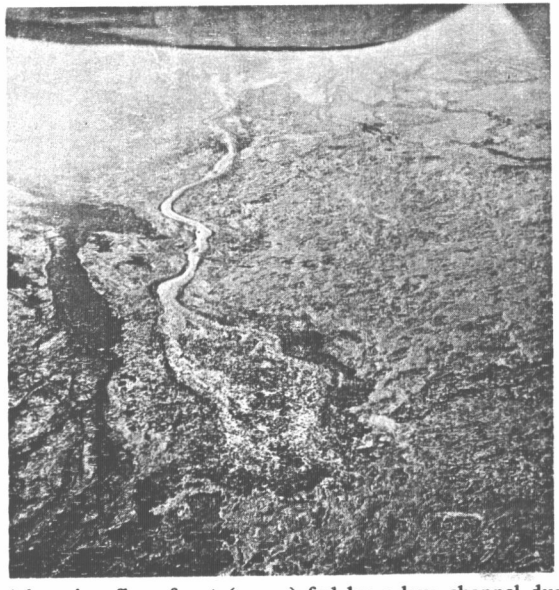


Fig. 7-14. Advancing flow front (arrow) fed by a lava channel during August 1970 eruptions of Mauna Ulu. Alae Crater lava lake is visible in the upper right. (*NASA-Ames photograph by Ronald Greeley, August 1970.*)

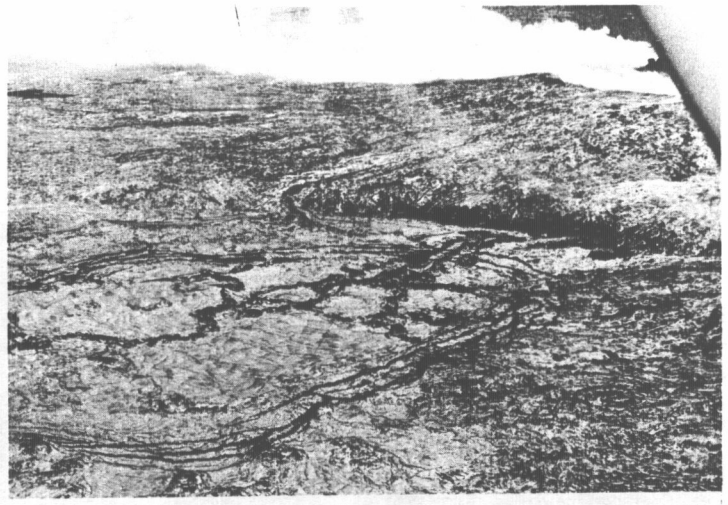


Fig. 7-15. View across Alae Crater toward Mauna Ulu (top right) shortly after the August 1970 partial drainage of the lava lake that filled Alae Crater (Greeley, 1971; see also Swanson and Peterson, 1972). (*NASA-Ames photograph by Ronald Greeley, August 1970.*)

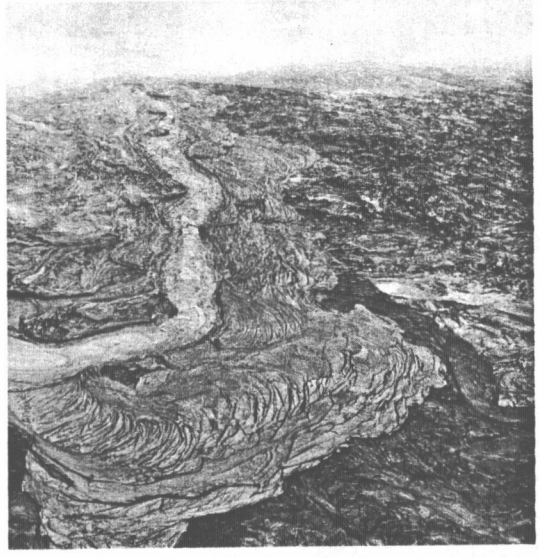


Fig. 7-16. View of an active lava channel which lead from a summit vent of Mauna Ulu (out of view to the lower left) to Alae Crater (top). Repeated overflows (right side of channel) resulted in the formation of natural levees along the banks of the channel. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

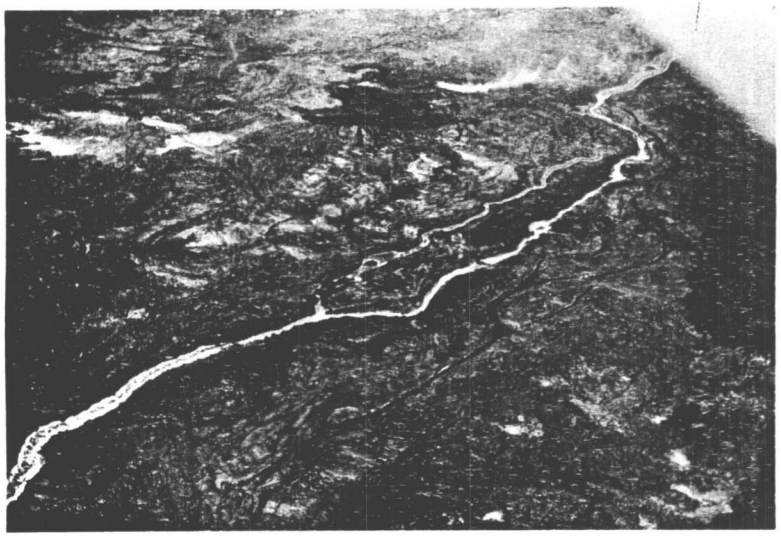


Fig. 7-17. Lava flow channels with a "cut-off" branch, during 1970 Mauna Ulu eruptions. Note the inactive, "abandoned" channel that parallels the active flow. (*NASA-Ames photograph by Ronald Greeley, August 1970.*)

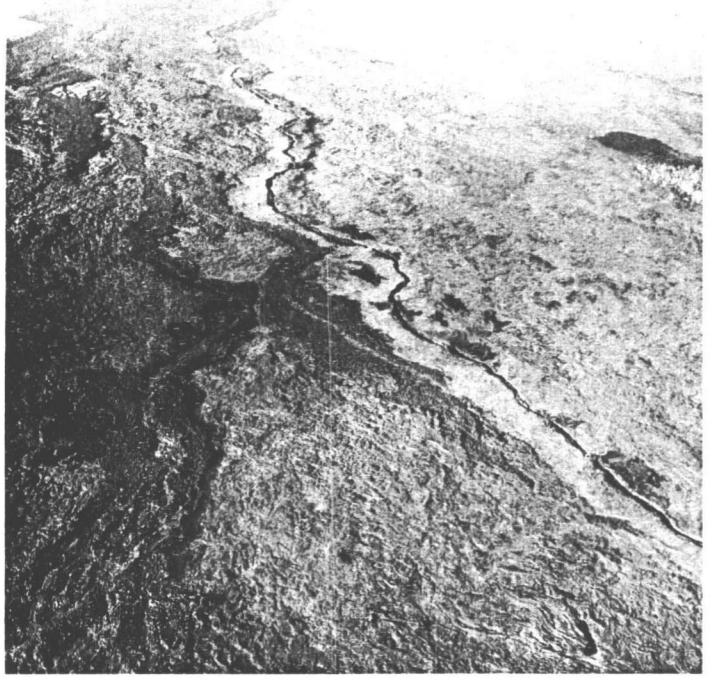


Fig. 7-18. Aerial view of a lava channel formed in pahoehoe lavas from Mauna Ulu. Note the broad ridge along the axis of the channel that has resulted from the accretion of lava by overflows from the channel. (*Photograph by Ronald Greeley, University of Santa Clara, June 1974.*)

Fig. 7-19. Summit vent of Mauna Ulu two days after the November 1973 eruption at Pauahi Crater. The lava lake in the western (far) end of the trench subsided about 40 m (*Photograph by Ronald Greeley, University of Santa Clara, November 1973.*)

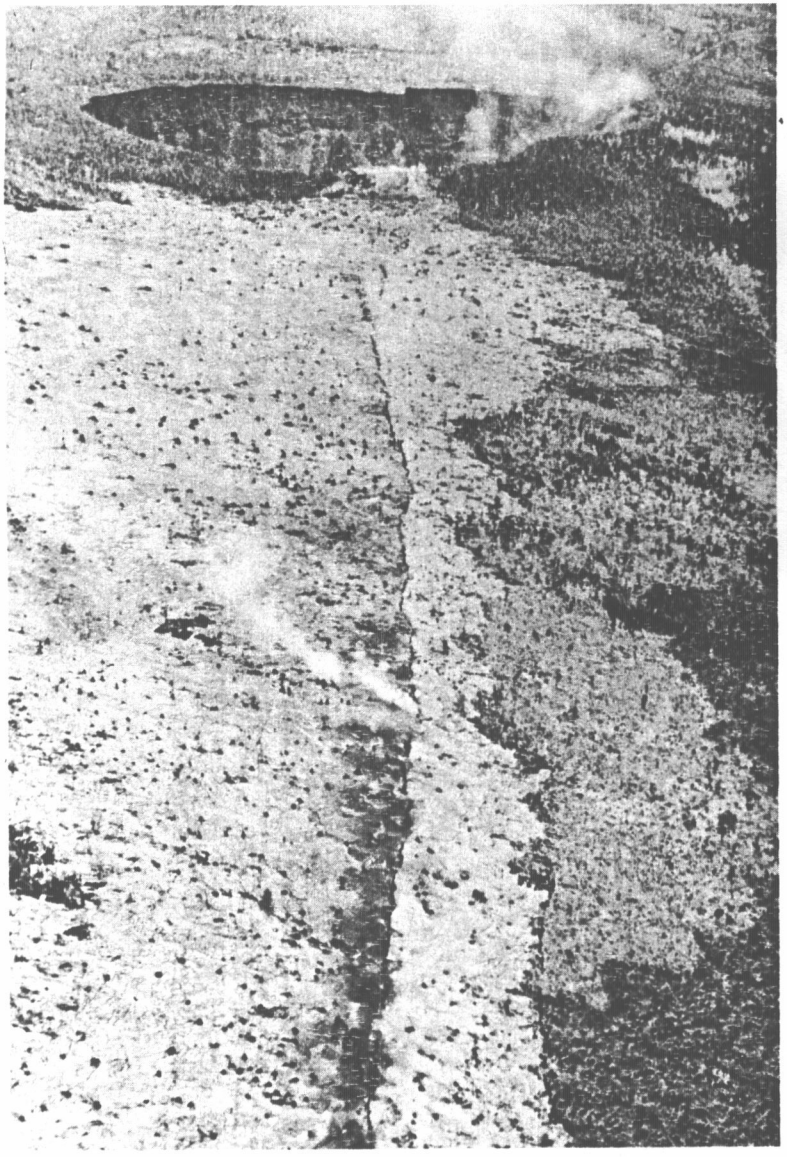


Fig. 7-20. View westward along a fissure and flow that formed in November 1973. Pauahi Crater is in background (see Fig. 7-21). (*Photograph by Ronald Greeley, University of Santa Clara, November 1973.*)

Fig. 7-21. View eastward across Pauahi Crater along the November 1973 fissures and flows, toward Mauna Ulu (fume on the horizon). (*U.S. Geological Survey - Hawaiian Volcano Observatory photograph by Robin T. Holcomb, December 1973.*)

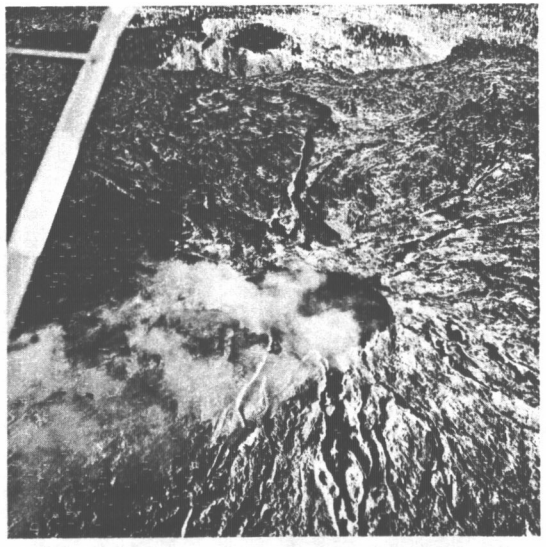


Fig. 7-22. Summit vent of Mauna Ulu in June 1974. Note the numerous lava channels and lava tubes radiating from the summit vent that resulted from repeated overflows of lava. Puu Huluhulu is at the top of the picture. (*Photograph by Ronald Greeley, University of Santa Clara, June 1974.*)

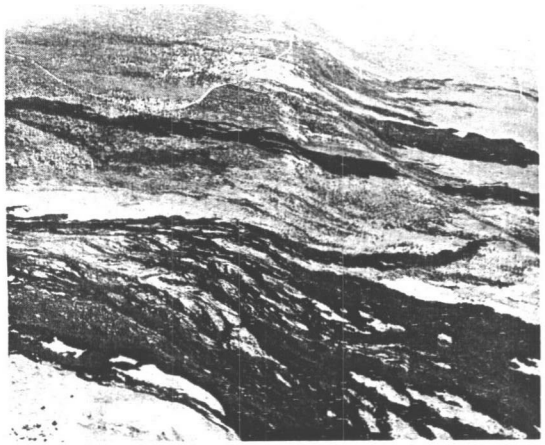


Fig. 7-23. View eastward along Poliokeawe Pali, one of the fault scarps of the Hilina system on the south slope of Kilauea. Converging with it from the right is another of the fault scarps, Holei Pali. The balck lava flows in the fore and mid-ground are from 1969 eruptions of Mauna Ulu. Chain of Craters Road in the background has been mostly covered by subsequent flows (from Macdonald and Abbott, 1970). (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

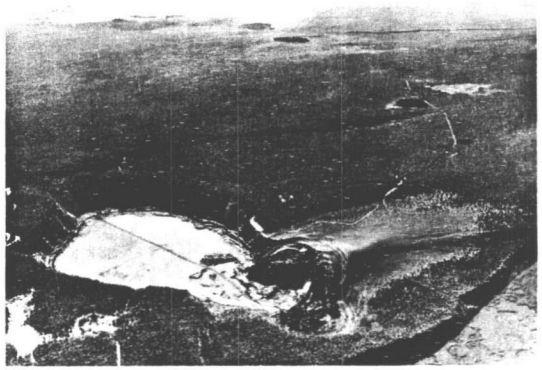


Fig. 7-24. View southeastward down Chain of Craters from Kilauea Iki in the left foreground (scarp of Kilauea Caldera is on right) to Lau Manu Crater, next small crater to the right of the road, Puhimau Crater next on left, Hiiaka Crater and Pauahi Crater, the last prominent craters visible, and eruptions at Mauna Ulu, identified by rising fume. Flows in Kilauea Iki are from the 1959 eruptions, as is the extensive tephra blanket that extends into the forest to the right of the crater. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

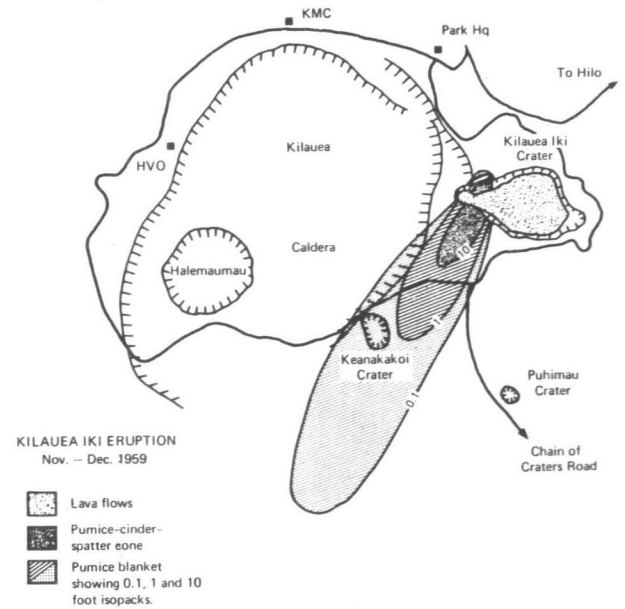


Fig. 7-25.

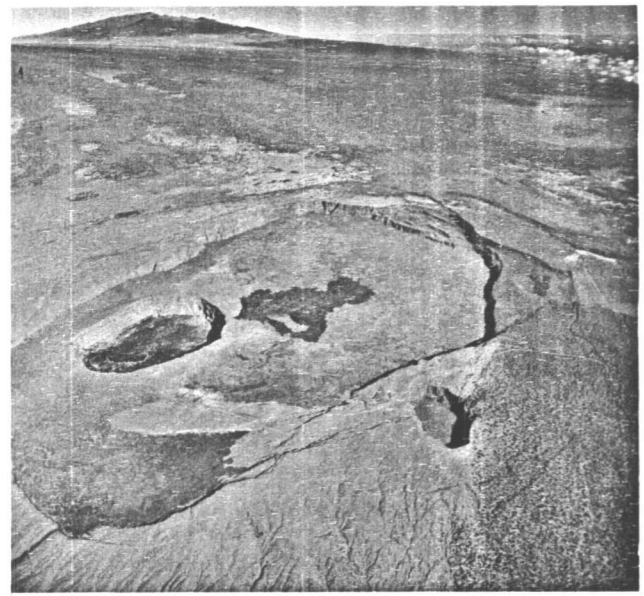


Fig. 7-26. View northward toward Mauna Kea across Kilauea Caldera and Halemaumau pit crater (left center). Flow of 1954 extends east from Halemaumau. (*U.S. Navy photograph, 1954.*)

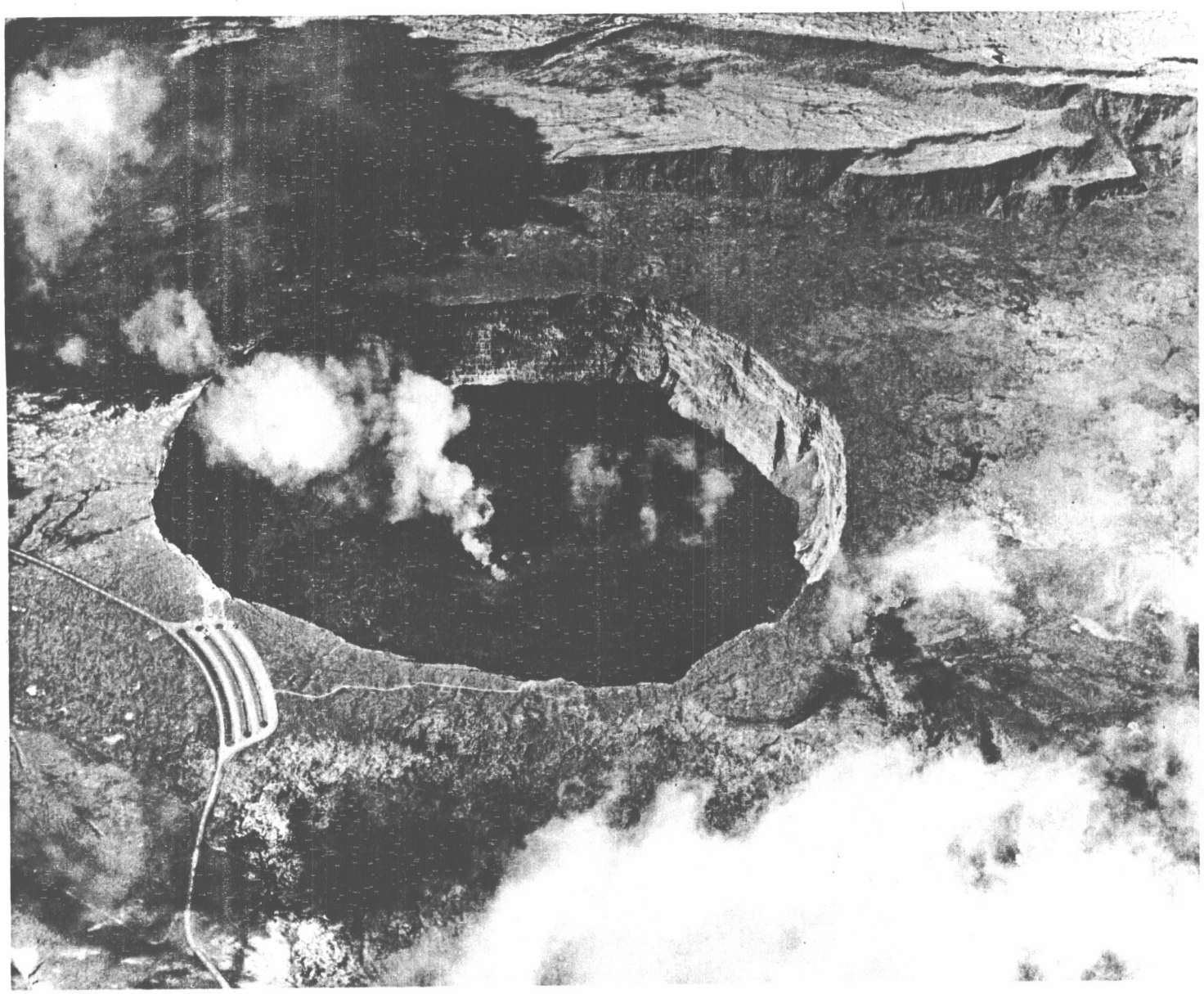
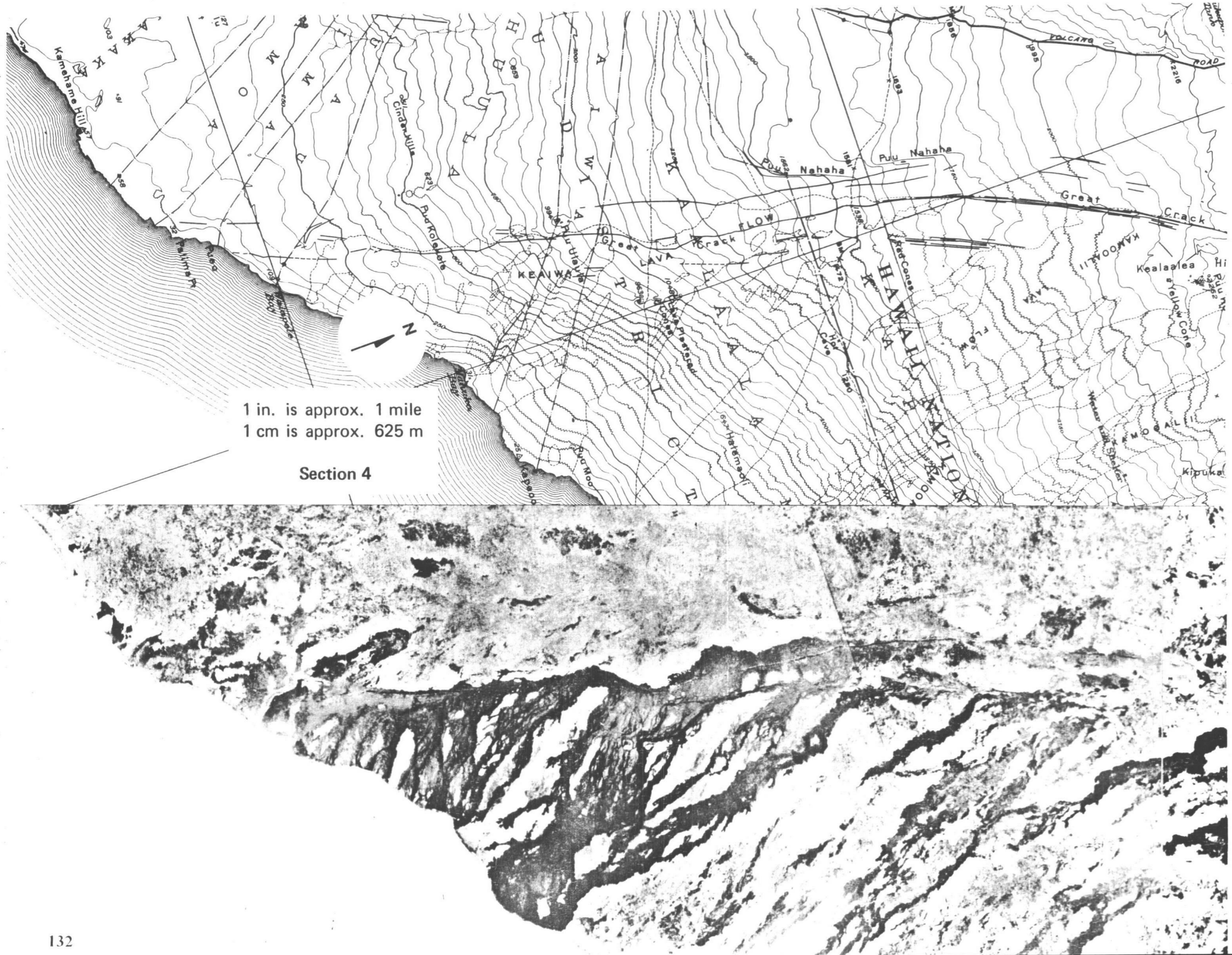
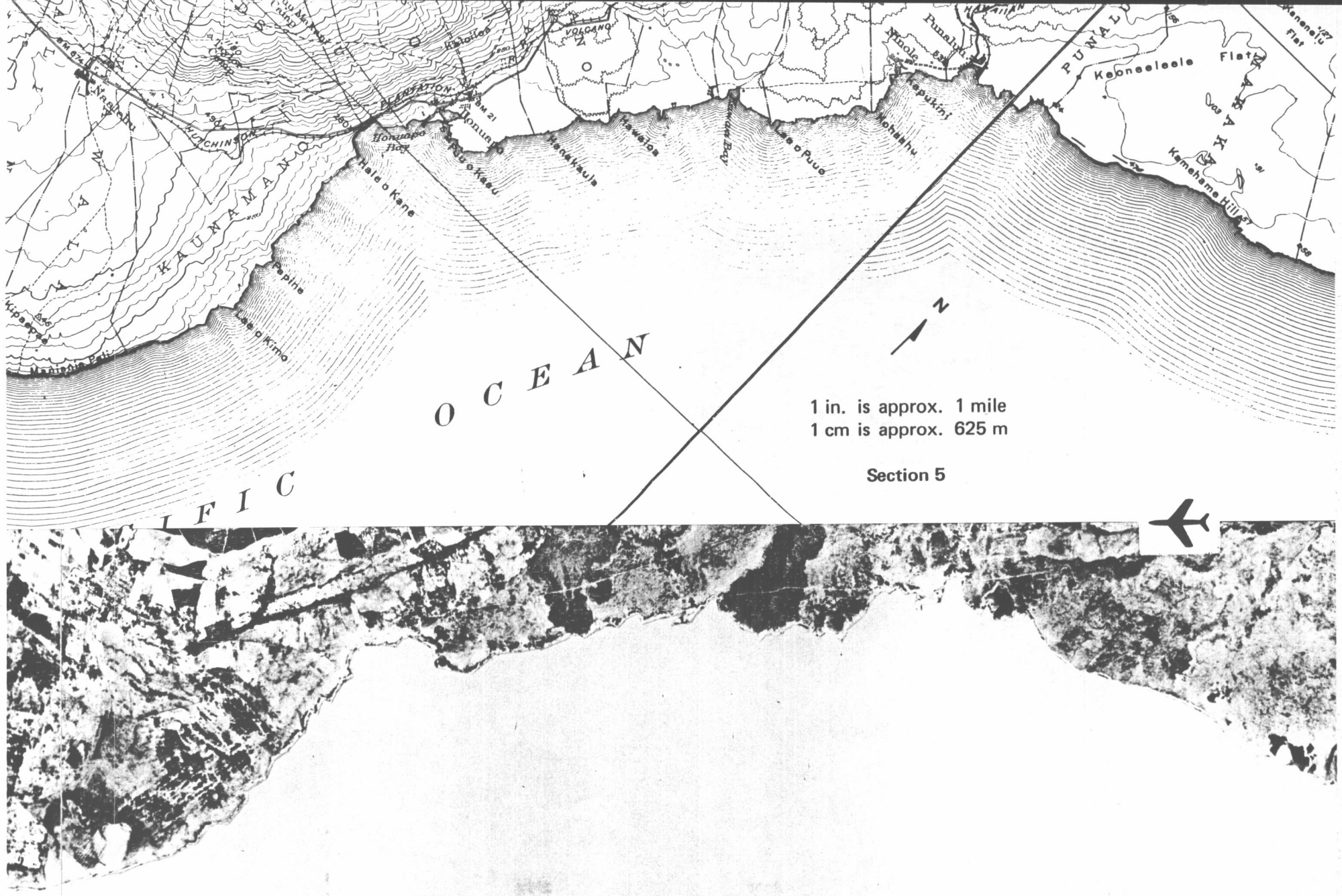


Fig. 7-27. Halemaumau pit crater on the floor of Kilauea Caldera on November 15, 1967, during an eruption. U.S. Geological Survey-Hawaiian Volcano Observatory is on caldera rim, upper right. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)


1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 4

PARK
TRAIL
Kawaikoholi WATERSHED
Kilauea Iki
Crater
Waldron Ledge
Kilauea
Mauna Loa
Mauna Loa Trail
Observatory
Volcano House
Volcano Village
Kilauea Military Camp
Kilauea Iki Trail
Crater Rim Drive
Kilauea Iki Overlook
Thurston Lava Tube
Nahuku
Devastation Trail
Pauahi Crater
Keanakakoi Crater
Kilauea Caldera
Kilauea Caldera Trail
Kilauea Caldera Overlook
Kilauea Overlook
Uwekahuna Bluff
Uwekahuna
Jaggar Museum
Hawaiian Volcano Observatory
Crater Rim Trail
Kilauea Iki Crater
Halemaumau Crater
Halemaumau
Halemaumau Trail
Halemaumau Overlook
Waldron Ledge
Kilauea Iki
Kilauea Iki Trail
Kilauea Iki Overlook
Thurston Lava Tube
Nahuku
Devastation Trail
Pauahi Crater
Keanakakoi Crater
Kilauea Caldera
Kilauea Caldera Trail
Kilauea Caldera Overlook
Kilauea Overlook
Uwekahuna Bluff
Uwekahuna
Jaggar Museum
Hawaiian Volcano Observatory
Crater Rim Trail
Kilauea Iki Crater
Halemaumau Crater
Halemaumau
Halemaumau Trail
Halemaumau Overlook

LAVA FLOW
KAMAOA
HOMESTEADS
PUUEO
KAWELA
KIOLAKAA
WAIOHINU
Puu Lohena
Puu Ulgulu
Puu Mahana
Kahawai
Kolonio
Pohoki Nui
Puu Hulunulu
Waiohinu Road
Kaalualu
Waiohinu
Kaalualu Road
Kaalualu Bay
Lua o Palahemo
Lua Makaiaiu
Kaalualu Pt.
Kaalualu Beach
Waiohinu Pt.


KAUMANO
Kaloiloa
VOLCANO
PLANTATION
Honuapo Bay
Hale o Kane
Pepiha
Kipapa
Punaluu
Hinole
Kapukini
Kehaahu
Kawaiea
Hanakaula
Kaalualu Bay
Kaa o Puua
PUNALUU
Kaheaeleele
Flat
Kaheaeleele Hill
Kanenelu
Flat
OCEAN
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 5

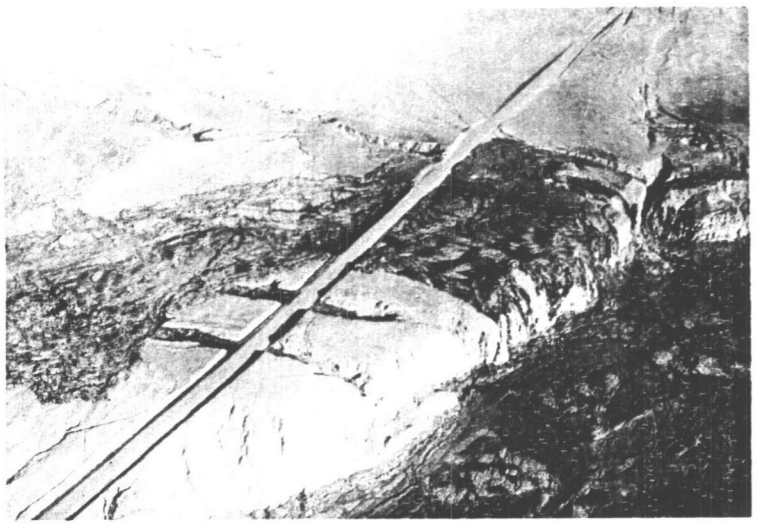


Fig. 7-28. View of the western end of Kilauea Caldera where the September 1971 fissure flows crossed Crater Rim Road and flowed onto the caldera floor. (*Photograph by Ronald Greeley, University of Santa Clara, June 1974.*)

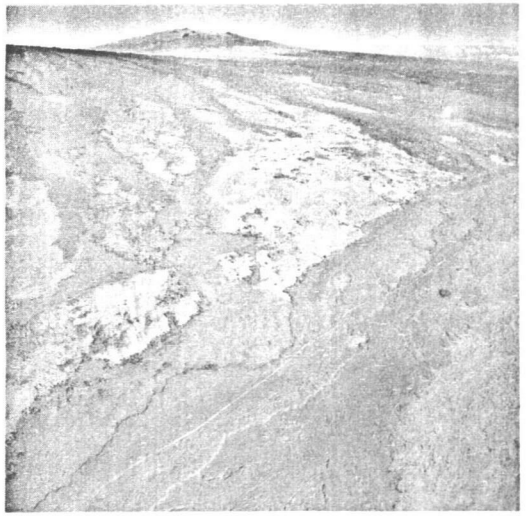


Fig. 7-29. View northwestward toward Mauna Kea across part of the Ka'u Desert (lower right) and the northwest rift zone of Mauna Loa (left horizon, cutting across Mauna Kea). Older lava flows from Mauna Loa Volcano are transected by the younger Keamoku lava flows, also from Mauna Loa. Hawaii Route 11 cuts diagonally across the view and here is entirely on the Keamoku lavas. (*U.S. Navy photograph, 1954.*)

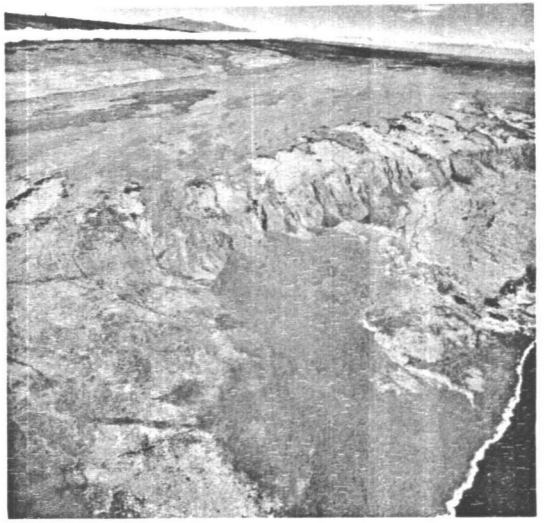


Fig. 7-30. View to the north across the Hilina Pali, one of the scarps of the Hilina fault system, toward Mauna Kea. Lava "fans" (wide, flat flows at the base of the pali) and talus cones of landslide debris are visible along the scarp. Mauna Iki is marked by the dark flows (left center). Kilauea is near the right horizon. (*U.S. Navy photograph, 1954.*)

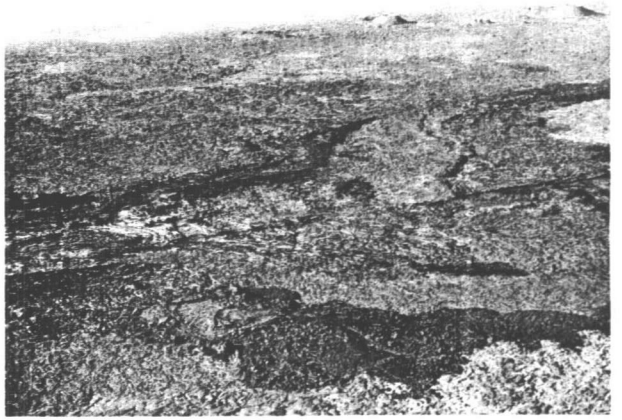


Fig. 7-31. View southward across the Ka'u Desert at Mauna Iki toward the Kamakaia Hills (tephra cones near the horizon). A prominent fissure of the southwest rift zone of Kilauea extends across the picture. (*U.S. Geological Survey-Hawaiian Volcano Observatory photograph by John Lockwood, 1974.*)

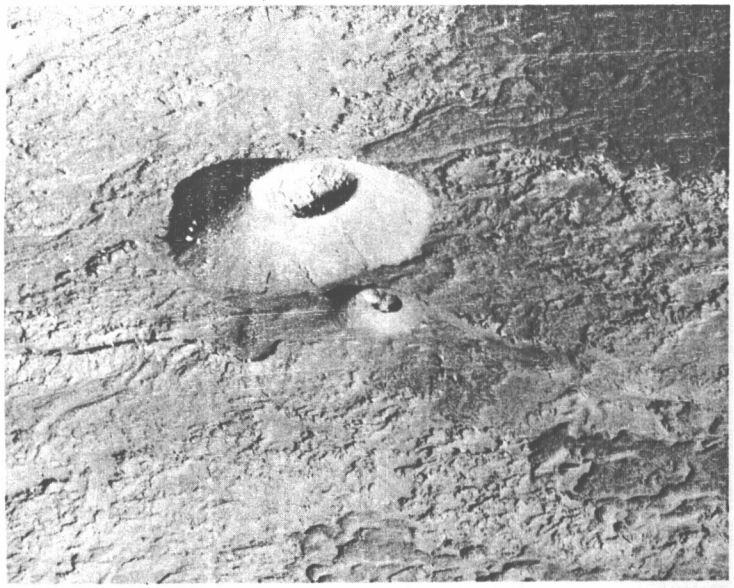


Fig. 7-32. Aerial view of one of the Kamakaia Hills, a tephra cone about 160 m in diameter and 32 m high. (*U.S. Geological Survey-Hawaiian Volcano Observatory photograph by John Lockwood, 1974.*)

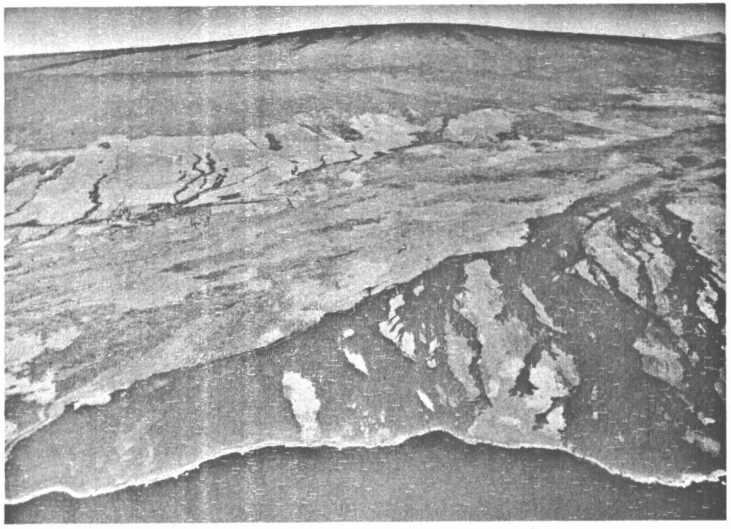


Fig. 7-34. View northwestward across part of the Ka'u Desert to Mauna Loa. Prominent dark lava in the foreground is the 1823 flow from the Great Crack. The lava was extremely fluid and flowed with great rapidity to the coast. (*U.S. Navy photograph, 1954.*)

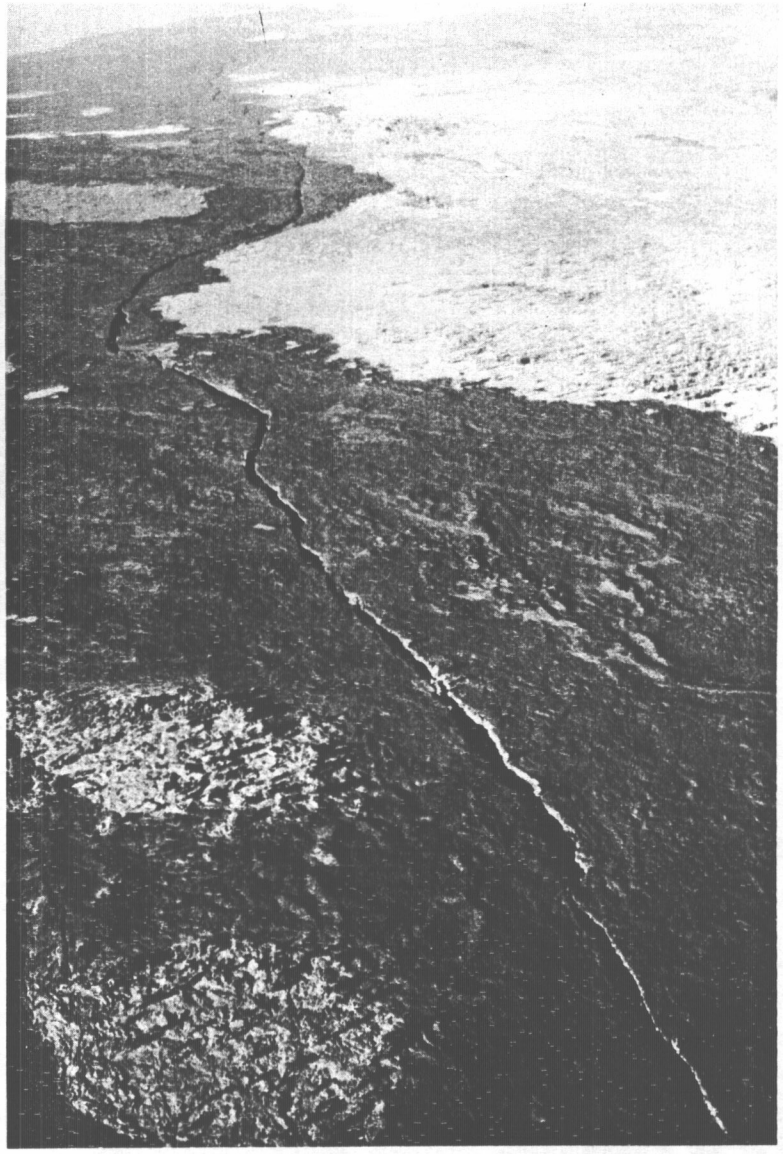
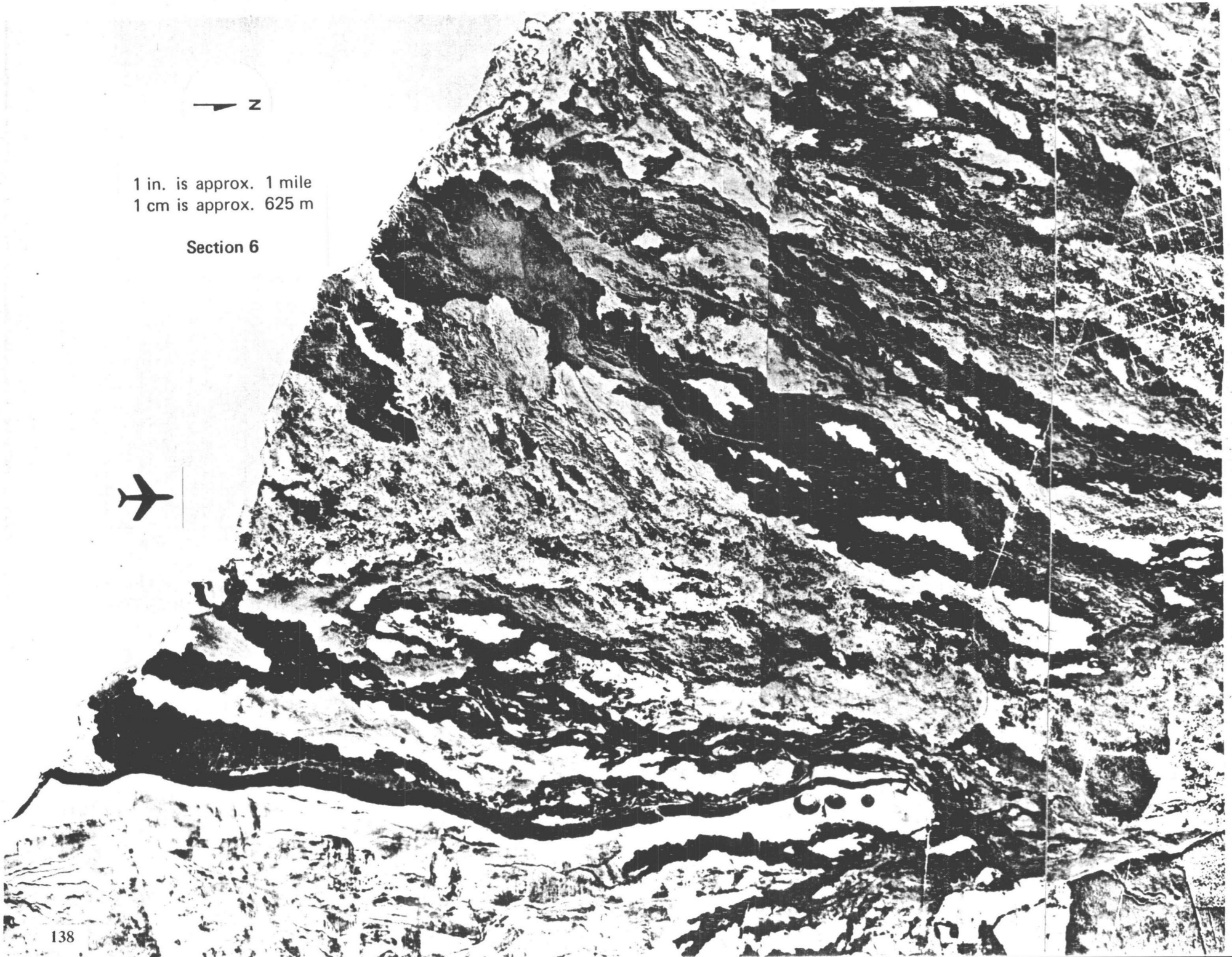
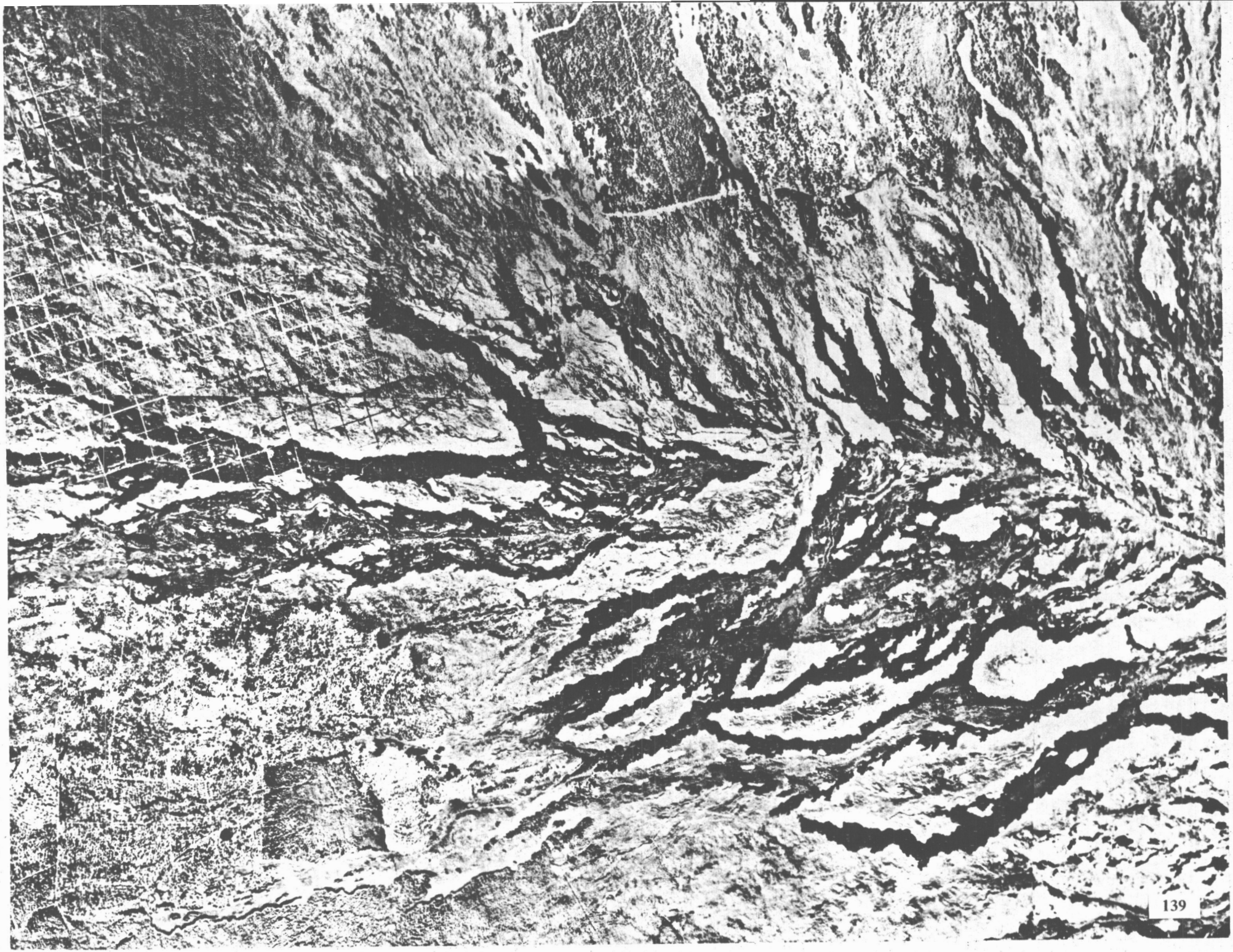
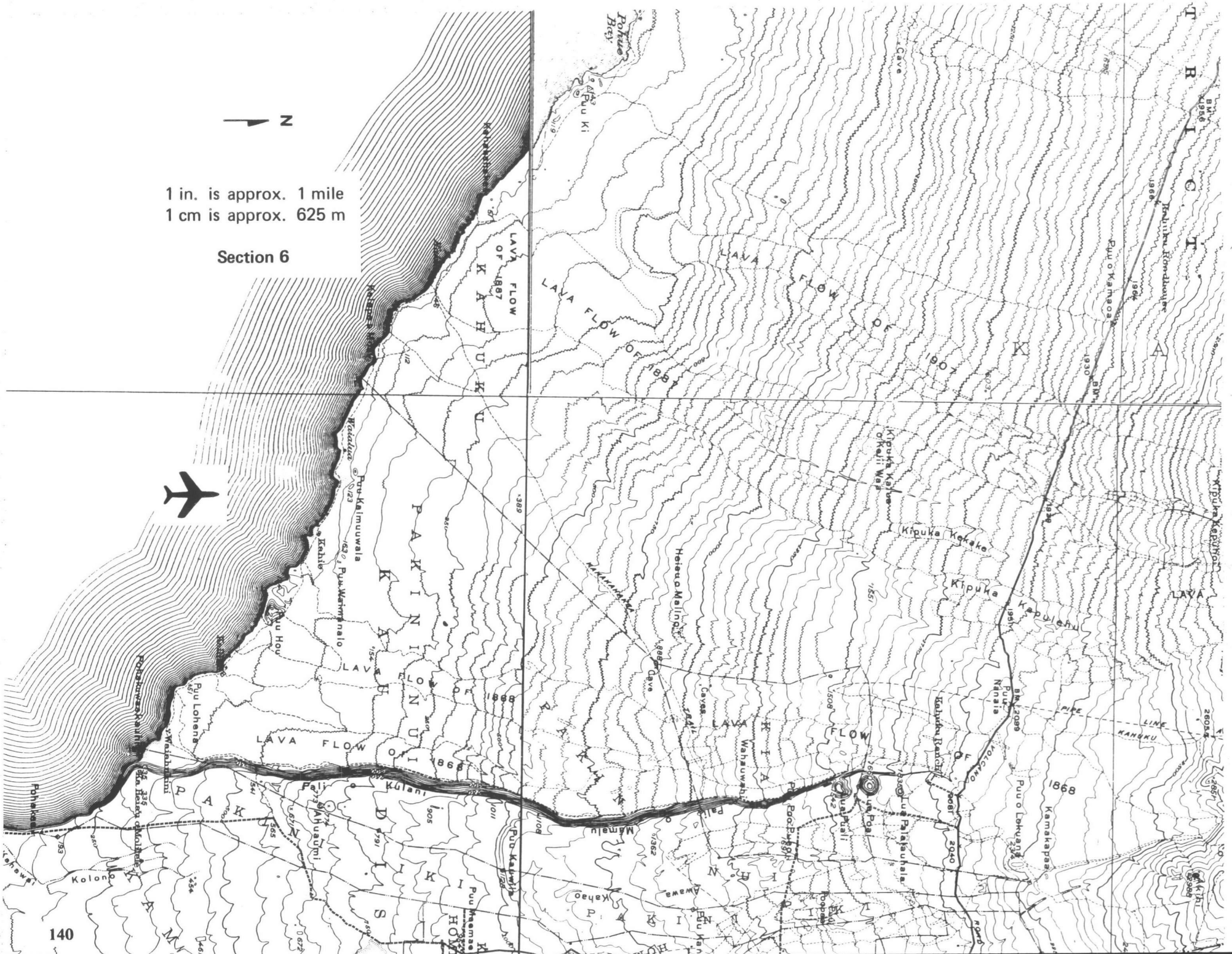
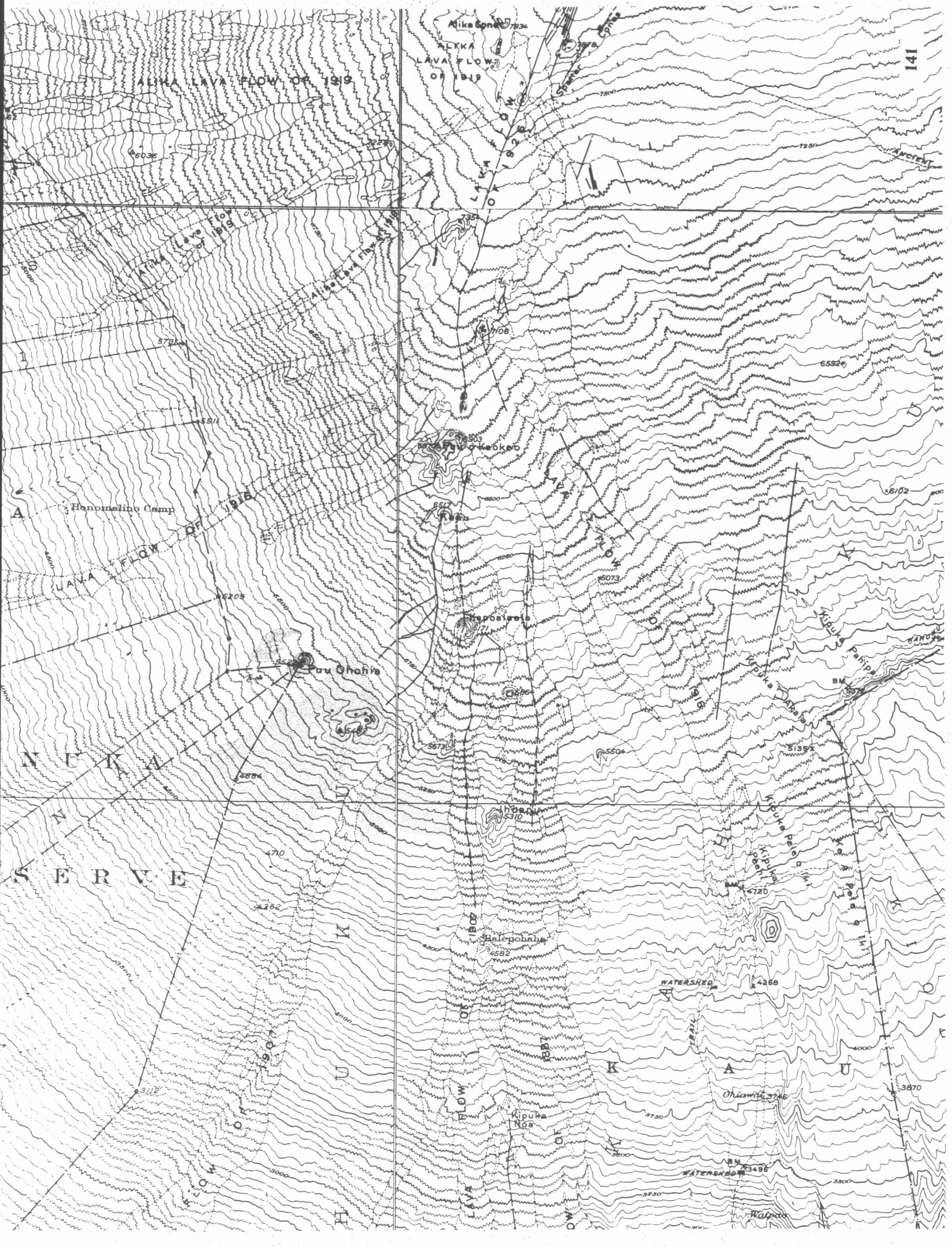


Fig. 7-33. View southwestward down the Great Crack and the 1823 lava flow. (*Photograph by Ronald Greeley, University of Santa Clara, June 1974.*)


N
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 6




N
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 6
Pohue Bay
Pu u Ki
Cave
LAVA FLOW OF 1887
KAHUKU
LAVA FLOW OF 1801
Kipuka Kaloko
Kipuka Kaloko
Kipuka Kaloko
Kipuka Kepuhi
Kipuka Kepuhi
LAVA
Pu u Kamaoa
Kahuku Roadhouse
PAKINI KAHUKU
Waiaulua
Pu u Kalmuuwala
Kehio
Pu u Hou
Pu u Wawaenalo
LAVA FLOW OF 1887
Heiau o Malino
Cave
Cave
LAVA
Wahauwahi
Pu u Nanala
Kahuku Ranch
Pipe Line
Kahuku
1868
Kamakapae
Pu u Lohena
Pohakuwaakauli
Waiahuimi
Pohakea
Kolonahaehae
Kolonahaehae
LAVA FLOW OF 1868
Pali
Kulani
Ahuaumi
Mamalu
Pu u Kaiwiki
Pu u Maemae
Pu u Kaiwiki
Pu u Kalaiwa
Pu u Kalaiwa
Pu u Kalaiwa


ALIKA LAVA FLOW OF 1919
Alika Cone
ALIKA LAVA FLOW OF 1919
Spatter Cone
Ancient
Alika Lava Flow of 1919
Alika Lava Flow of 1919
Honomalino Camp
LAVA FLOW OF 1919
Pau Ohohia
Okeokeo
Kipuka Pahipa
Kipuka Alaala
Kipuka Nea
Kipuka Nea
Hale-pohaha
WATERSHED
WATERSHED
Ohianiu
Kipuka Noa
Waiaua
NUKA
SERVE
141

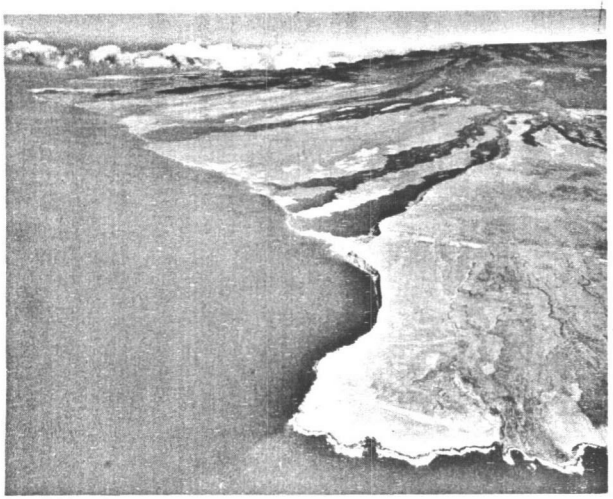


Fig. 7-35. View of South Point (foreground) toward the northwest. Dark lava flows are aa basalt from Mauna Loa (1868, 1887 flows). (*U.S. Navy photograph, 1954*)

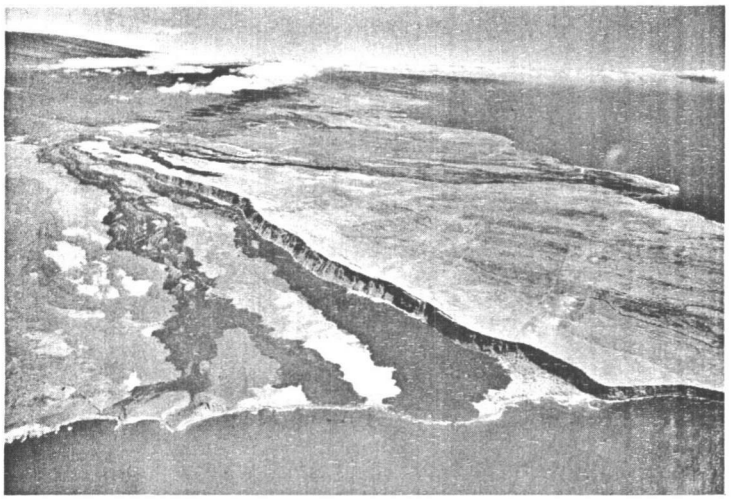


Fig. 7-36. View northeastward toward Mauna Loa summit (left horizon) along the Kahuku Pali (about 200 m high), formed by the Kahuku fault. The fault can be traced about 16 km on land and about 28 km out to sea. Three pit craters are visible on the upthrown side of the fault where the scarp disappears landward. The fresh lava flow at the base of the scarp is the 1868 flow from Mauna Loa. Puu Lou, a littoral cone, is on the coast where the 1868 flows entered the sea (lower left). (*U.S. Navy photograph, 1954.*)

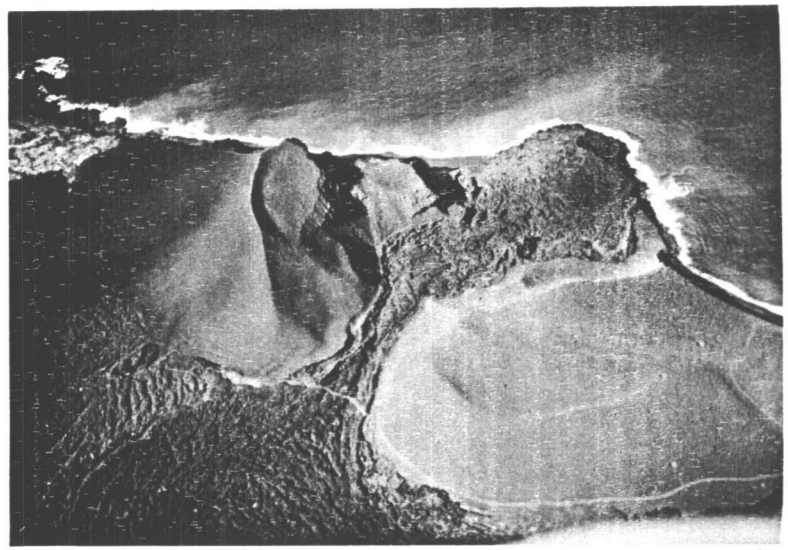


Fig. 7-37. Oblique aerial view of the littoral cone Puu Hou, a few kilometers west of South Point. The cone formed when 1868 lava flows from Mauna Loa entered the sea. (*Photograph by Ronald Greeley, University of Santa Clara, June 1974.*)

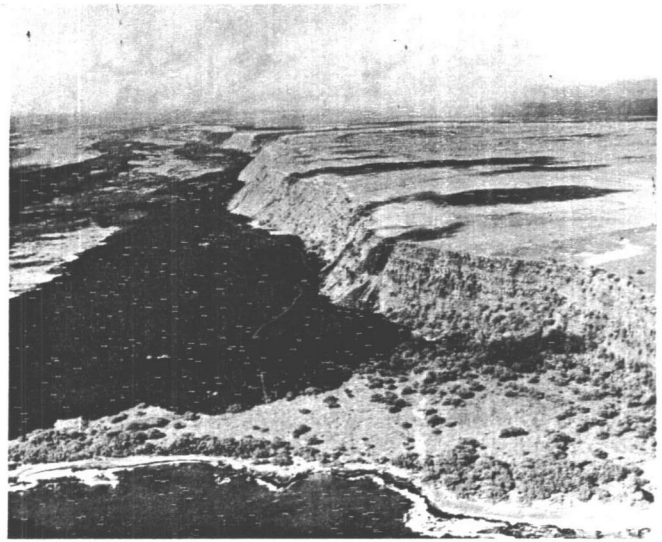


Fig. 7-38. South Point area, looking north along the Kahuku fault scarp and the 1868 aa flow. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

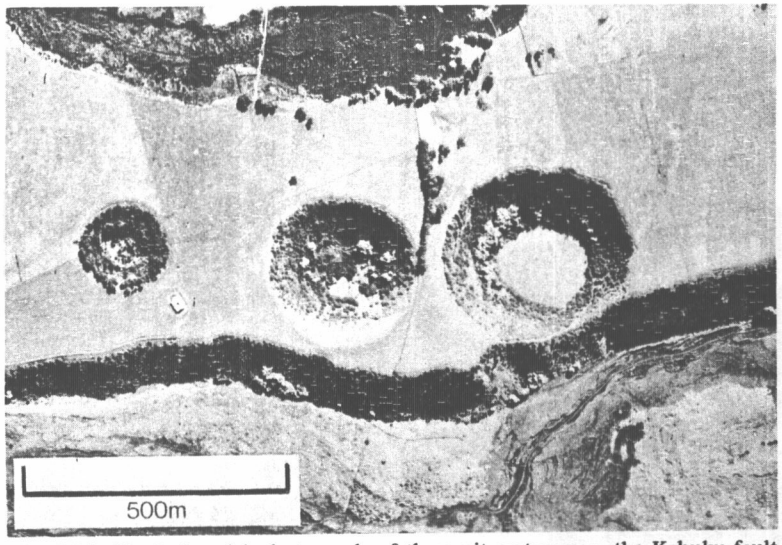


Fig. 7-39. Vertical aerial photograph of three pit craters near the Kahuku fault scarp. Craters from right to left are Lua Puali, Lua Poai, and Lua Palalauhala. The fresh lava flow at the base of the scarp is the 1868 flow from Mauna Loa. (*U.S. Dept. of Agriculture photograph, EKL-14CC-25, 1965.*)

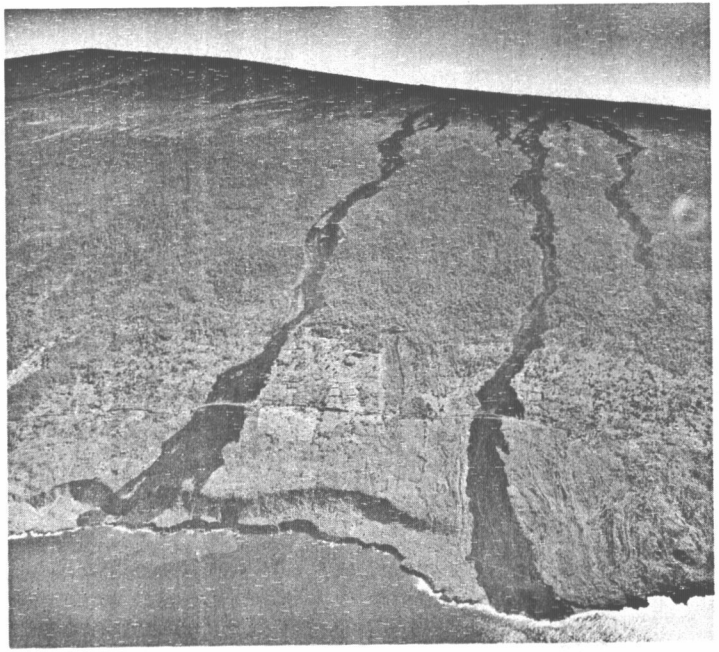


Fig. 7-40. View eastward toward the summit of Mauna Loa; southwest rift zone of Mauna Loa is approximately on the horizon. Dark aa flows are from the 1950 eruptions, which originated on the rift. Road paralleling the coast is Hawaii State Route 11. (*U.S. Navy photograph, 1954.*)

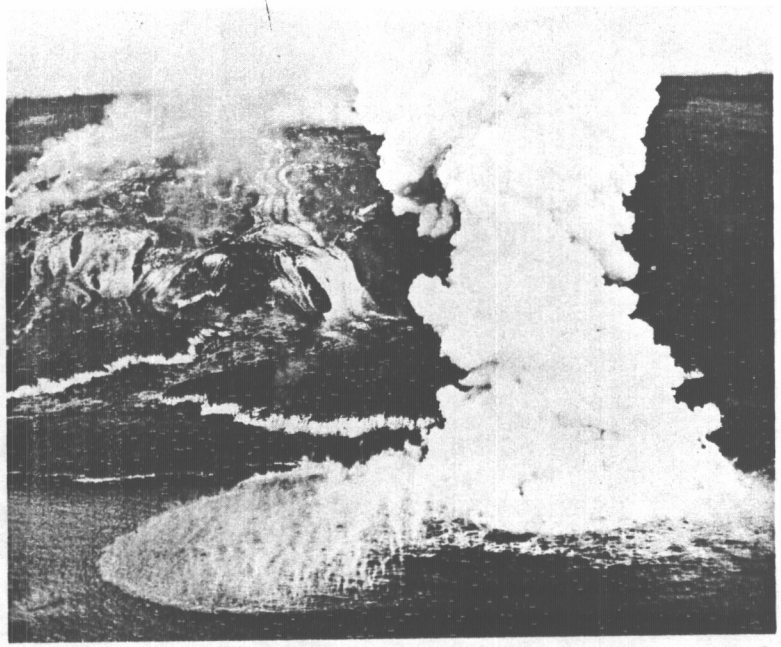
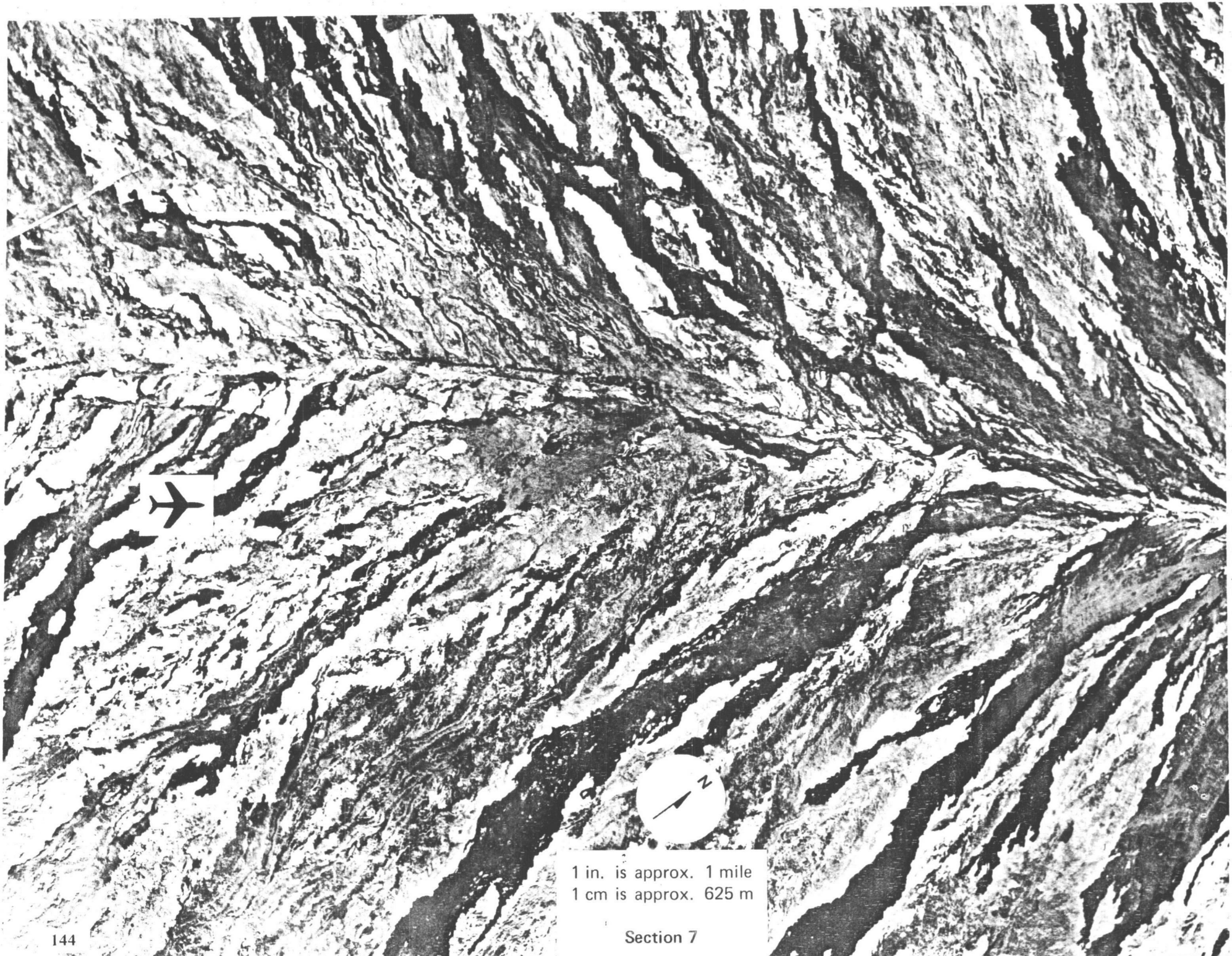
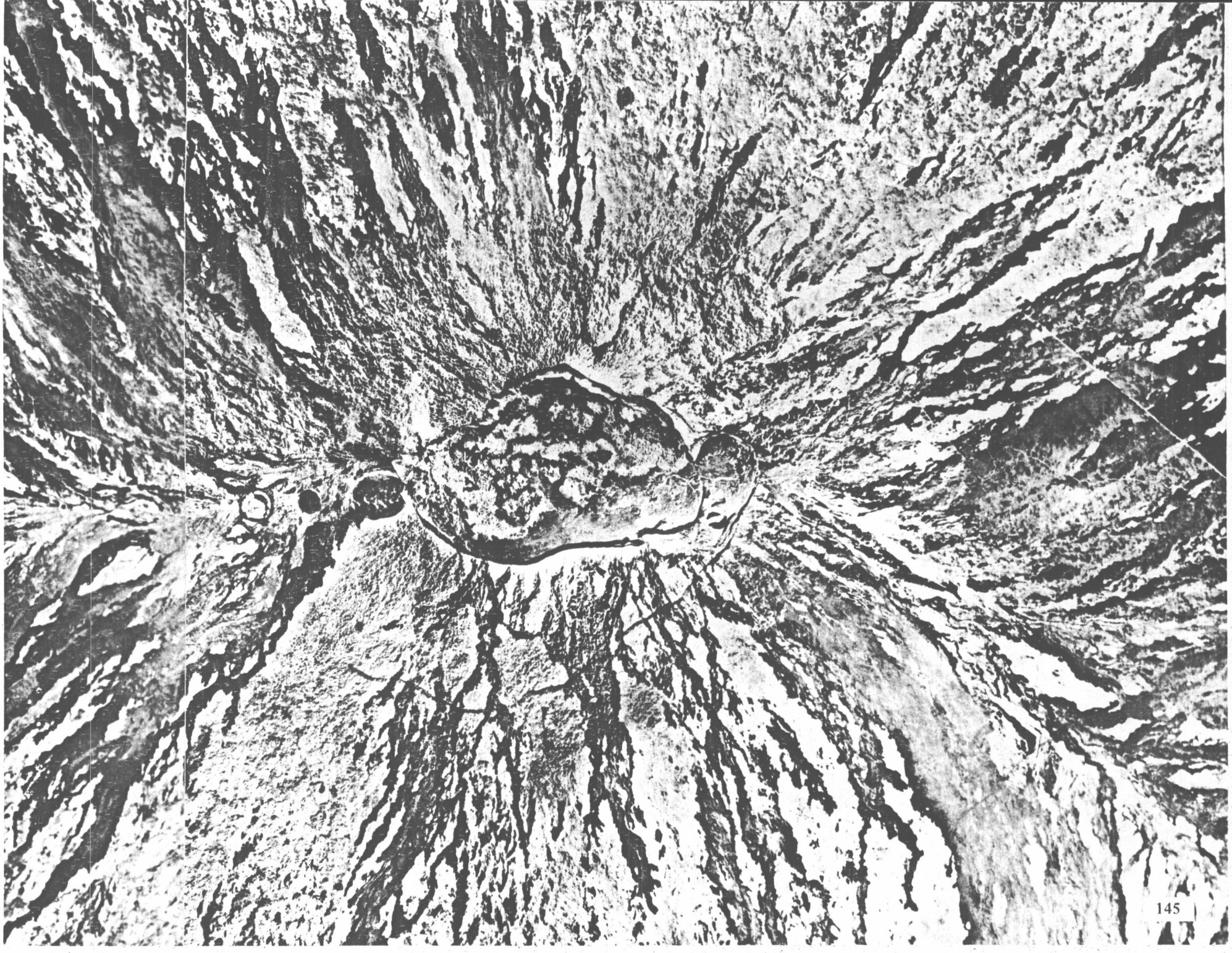


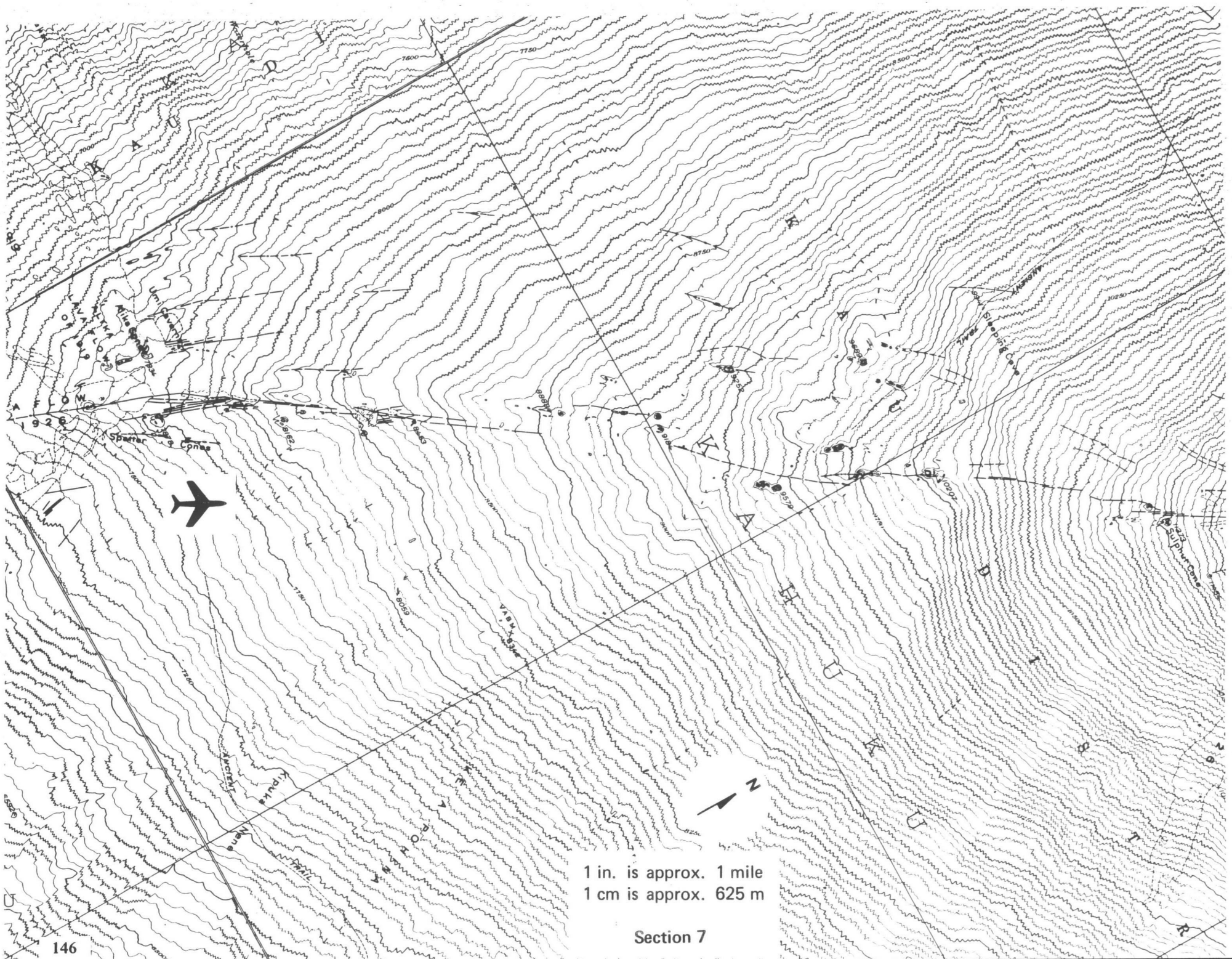
Fig. 7-41. Lava flow entering the ocean on the west side of Mauna Loa on June 2, 1950. Note the steam cloud rising from the ocean and the boiling water at its base. (*Photograph by Air National Guard, Hawaii.*)



1 in. is approx. 1 mile
1 cm is approx. 625 m

Section 7





Section 7

HAWAII NATIONAL PARK
KAHUKU UNIT
KAU DESERT
MAUNA LOA
KILAUEA
MOKUAWEOWEO CRATER
Pu'u Waenakonu
Lua Ioane
Portlo
Lua Hohonu
Lua Hou
Pohaku Hanaiele
Waterhole
Trail
Volcano House
Pukaulu
147

Fig. 7-42. View northeastward up the southwest rift zone to the summit of Mauna Loa. (*NASA-Ames photograph by Mike Lovas, 1970.*)

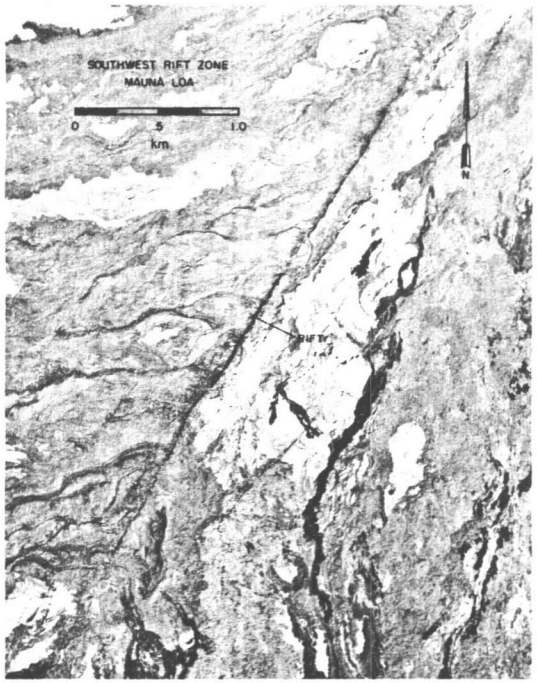


Fig. 7-43. Vertical photograph of the southwest rift zone of Mauna Loa Volcano showing pyroclastic cones, lava flows, and associated lava tubes and channels, all typical of shield volcanoes. (*U.S. Dept. of Agriculture photograph, 1965.*)

Fig. 7-44. Southwest rift zone of Mauna Loa showing braided lava channels that developed in pahoehoe lavas erupted from fissures. Fissure zone trends diagonally from upper right and is identified by cinder-spatter cones (*NASA-Ames photograph by Ronald Greeley, 1970.*)

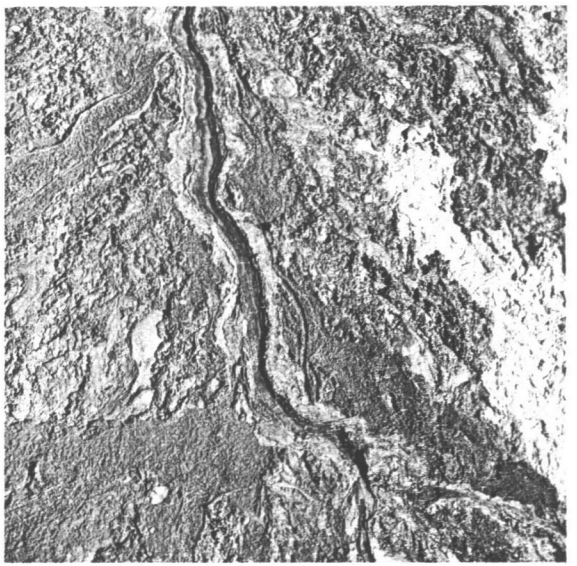


Fig. 7-45. Low-altitude view of a typical basaltic terrain, showing complex overlapping flows and flow units with textures ranging from pahoehoe (lightest toned flow) to aa (rubbly surface flows). One of the younger flows is identified by a partly collapsed lava tube a few meters wide. The lava tube apparently collapsed when the molten lava drained from the conduit, withdrawing support from a relatively thin crust. (*NASA-Ames photograph by Ronald Greeley, August 1970.*)

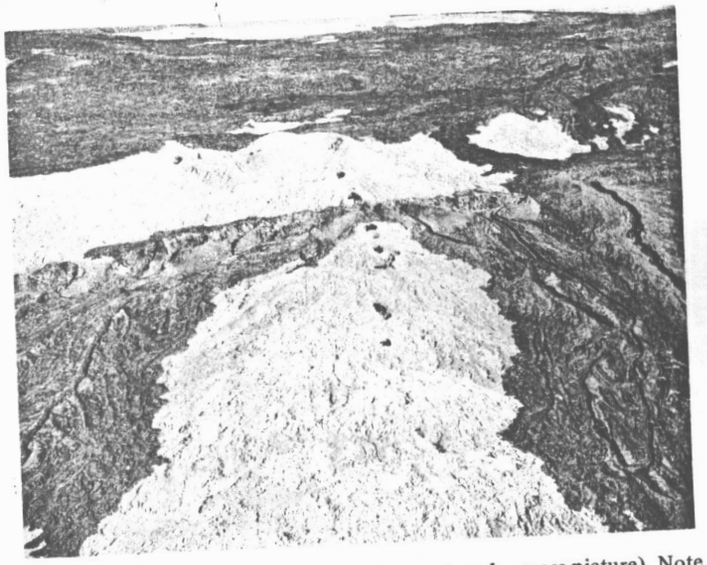


Fig. 7-46. Southwest rift of Mauna Loa (rift zone trends across picture). Note the partly collapsed lava tube that developed in flows originating from the base of the cinder spatter-cone in the center. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

Fig. 7-47. Southwest rift zone of Mauna Loa showing an elongate trench that developed along the rift. Note the fine-grained tephra to the right of the trench. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

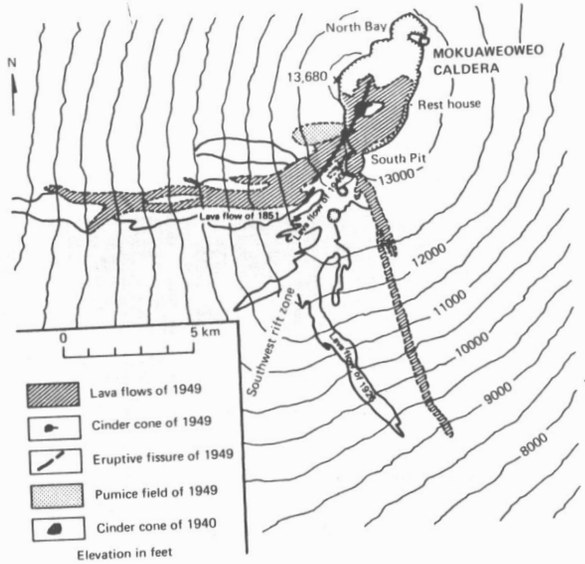


Fig. 7-48. Geologic sketch map of the summit of Mauna Loa Volanco showing the main features of the 1949 eruption (*from Macdonald and Orr, 1950*).

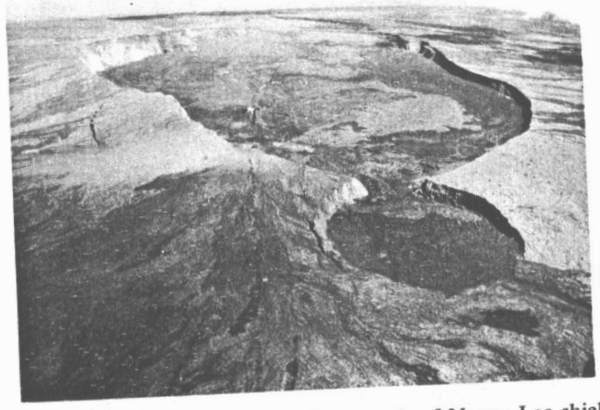


Fig. 7-49. View northeastward across the summit of Mauna Loa shield volcano and Mokuaweoweo Caldera and South Pit (lower right). (*U.S. Navy photograph contributed by Dale Cruikshank, University of Hawaii.*)

Fig. 7-50. View to the northwest across the summit of Mauna Loa toward Hualalai shield volcano. South Pit, partly filled with 1949 flows, is in the center; Mokuaweoweo Caldera is to right center. Summit of Haleakala, on the island of Maui is visible on the horizon above clouds. (*U.S. Navy photograph, 1954.*)

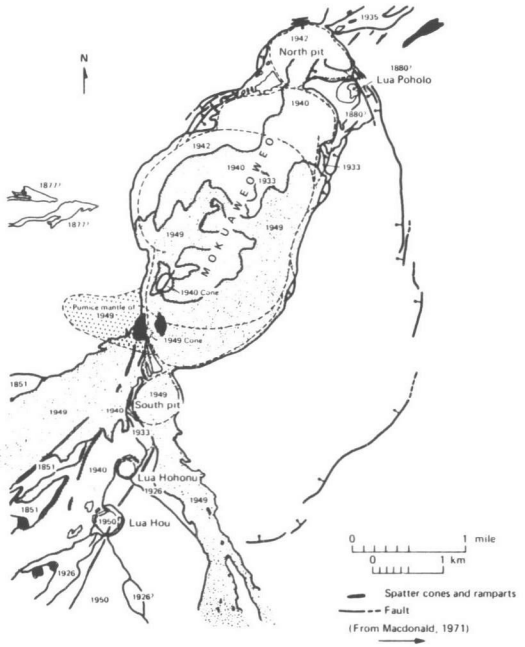


Fig. 7-51. Geologic sketch map of Mokuaweoweo Caldera and the upper part of the southwest rift zone of Mauna Loa Volcano showing the primary historic lava flows (*after Macdonald, 1971*).

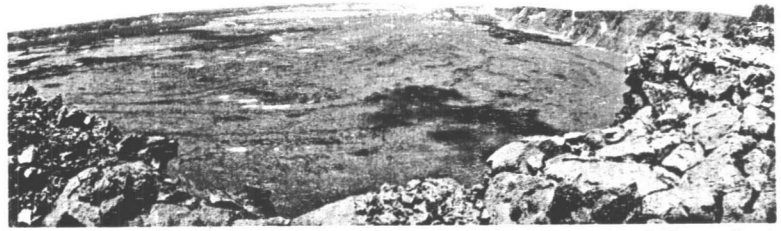


Fig. 7-52. Panoramic view of Mokuaweoweo Caldera (summit of Mauna Loa) toward the south. The breach into South Pit shows as a notch in the horizon. White patches are snow. (*Photograph by Dale Cruikshank, University of Hawaii.*)

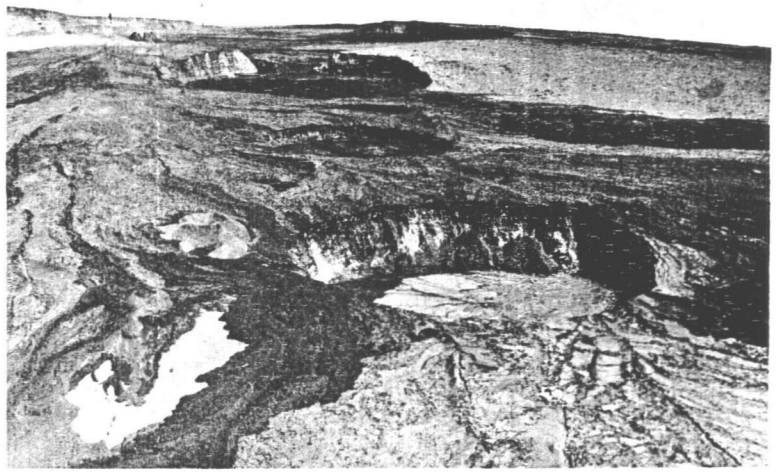


Fig. 7-53. View northeastward across the summit of Mauna Loa. In order, beginning in the front are Lua Hou pit crater (dark lava to its left is the 1940 lava flow), Lua Hohonu pit crater, partly filled with 1940 flows, and South Pit, which opens onto the floor of Mokuaweoweo Caldera. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

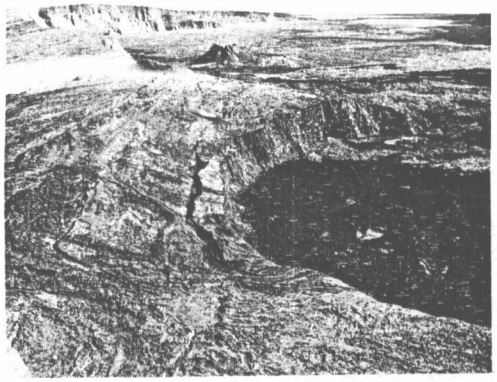


Fig. 7-54. View northeastward across the summit caldera (Mokuaweoweo) of Mauna Loa. Note the fractures and incipient slumping along the margin of South Pit, right center. In top center is the 1940 cinder-spatter cone on the floor of the caldera. (*NASA-Ames photograph by Mike Lovas, 1970.*)

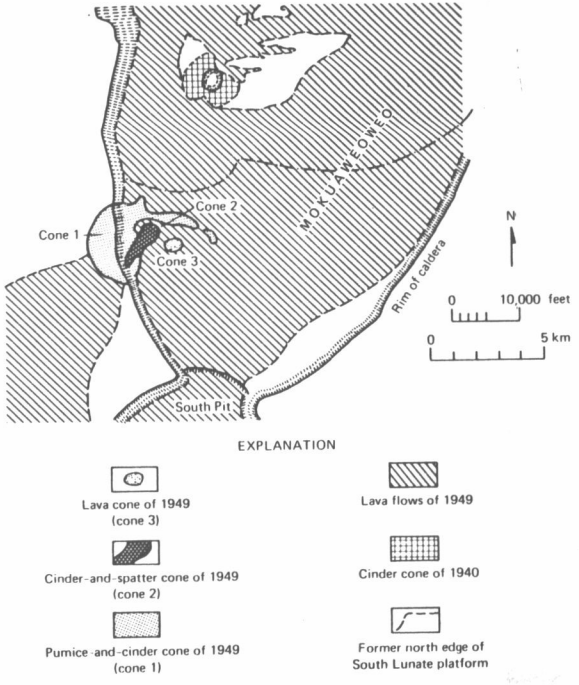


Fig. 7-55. Geologic sketch map of the southern end of Mokuaweoweo Caldera showing some of the lava flows and structures of the 1949 eruption (*from Macdonald and Orr, 1950*).

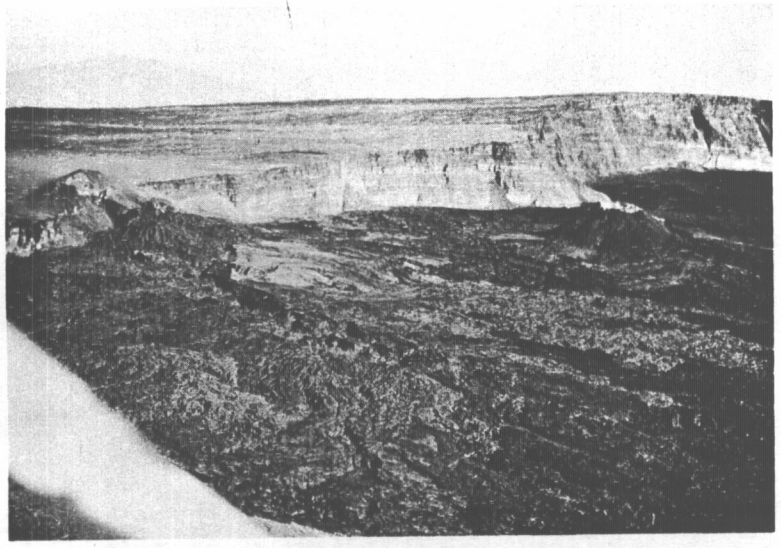


Fig. 7-56. View northeastward across part of Mokuaweoweo Caldera toward Mauna Kea on the left horizon. Fissure and cone in left center are from the 1949 eruption. (*NASA-Ames photograph by Ronald Greeley, August 1970.*)

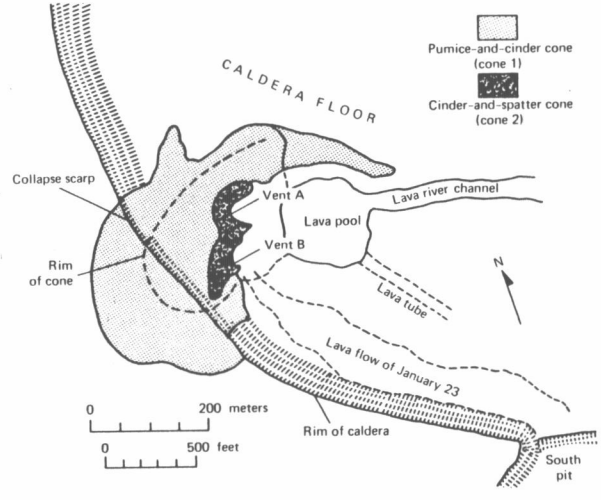


Fig. 7-57. Map of part of Mokuaweoweo Caldera showing the cone area of the 1949 eruption (*from Macdonald and Orr, 1950*).

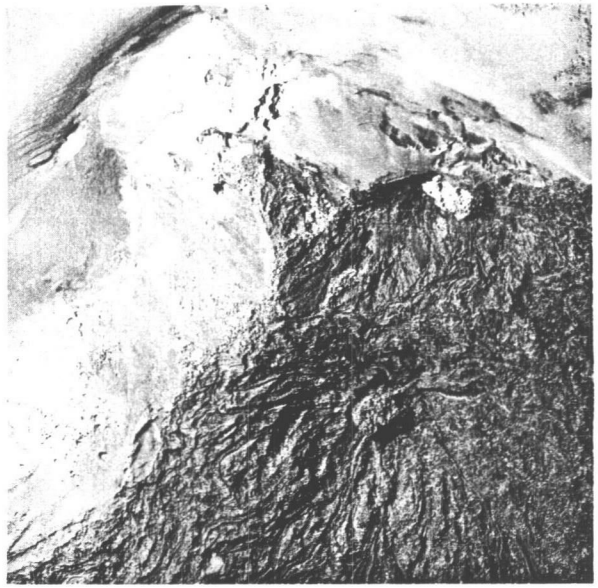


Fig. 7-58. View of the 1949 cinder-spatter cone area at the southwest edge of Mokuaweoweo Caldera (see also Fig. 7-56). Vent A is in the right center, vent B is in the foreground. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

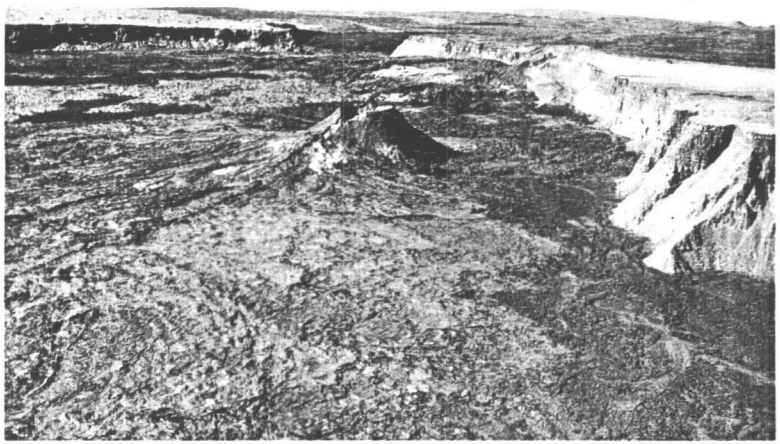


Fig. 7-59. ,View southwestward across the floor of Mokuaweoweo Caldera and the cinder-spatter cone of 1940. Note the fracture that transects the cone. (*NASA-Ames photograph by Mike Lovas, 1970.*)

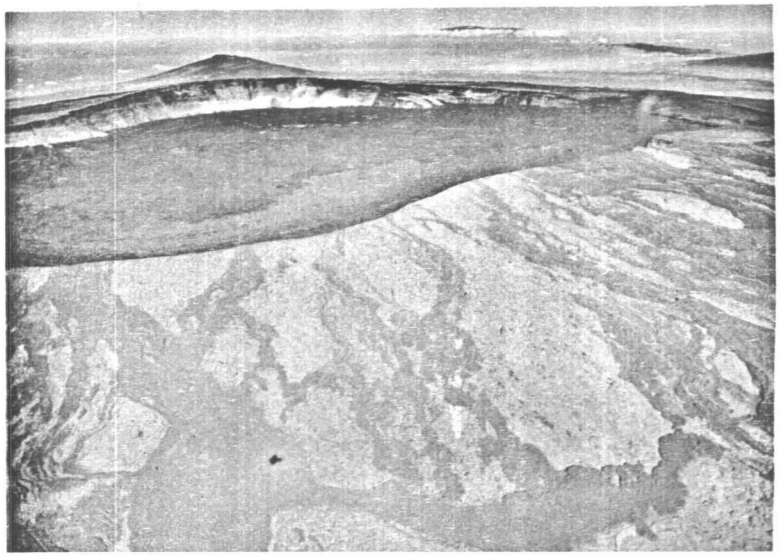


Fig. 7-60. View to the northwest across the summit of Mauna Loa and Mokuaweoweo Caldera; prehistoric flows are in the foreground. (*U.S. Navy photograph, 1954.*)

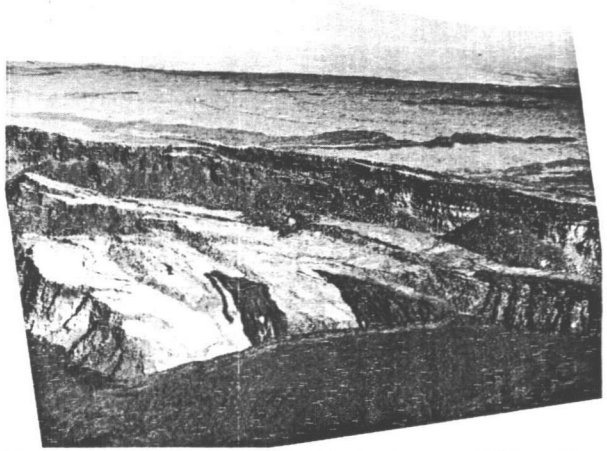


Fig. 7-61. View northward across the rim of Mokuaweoweo Caldera, Mauna Loa summit, showing the slump blocks and fractures. Lower slump blocks are submerged beneath lava flows of 1942. Note the fissure flows that apparently occurred along slump-block fractures. The small white building on the rim is a hiker's shelter. Mauna Kea Volcano is in the background. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

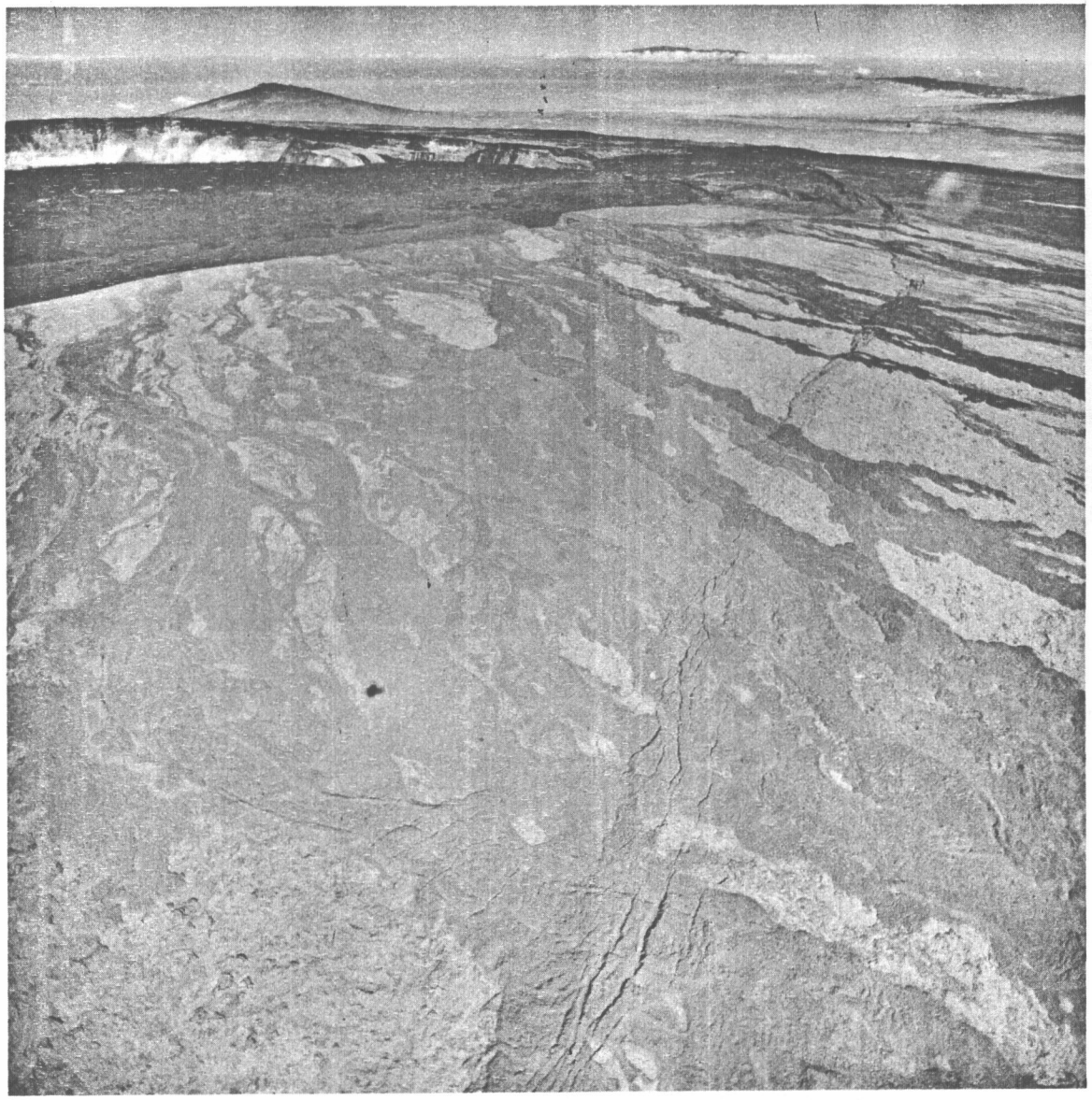
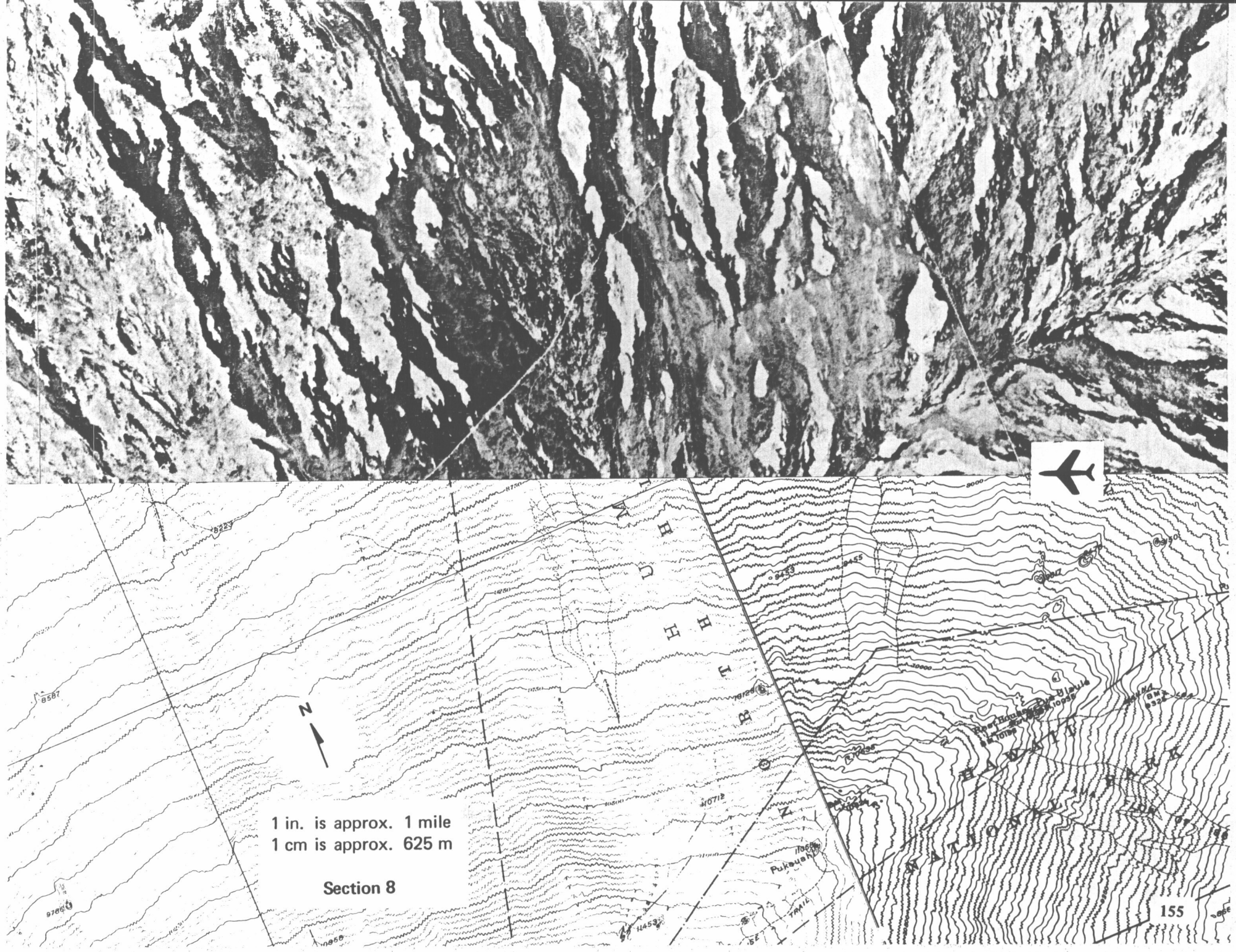
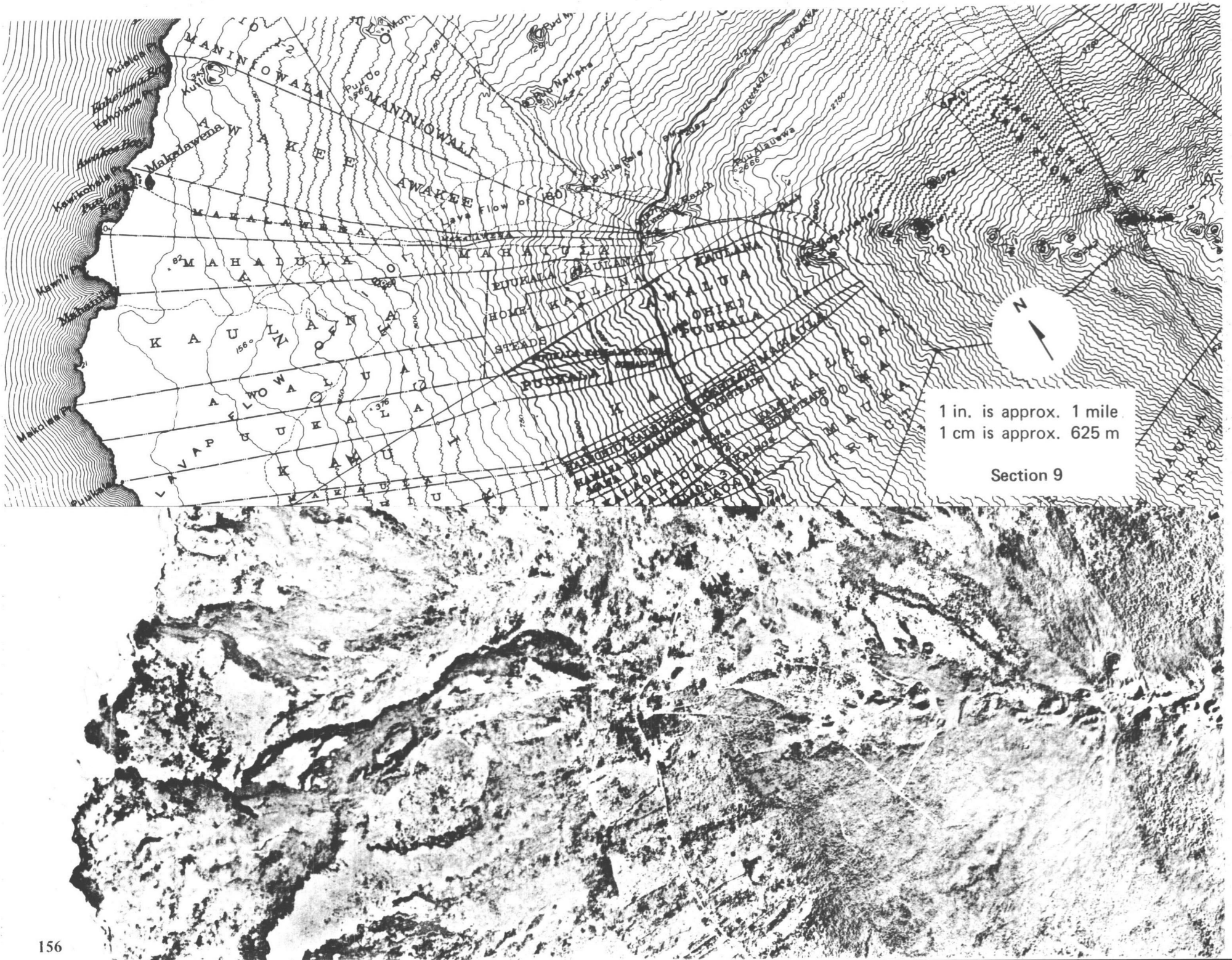


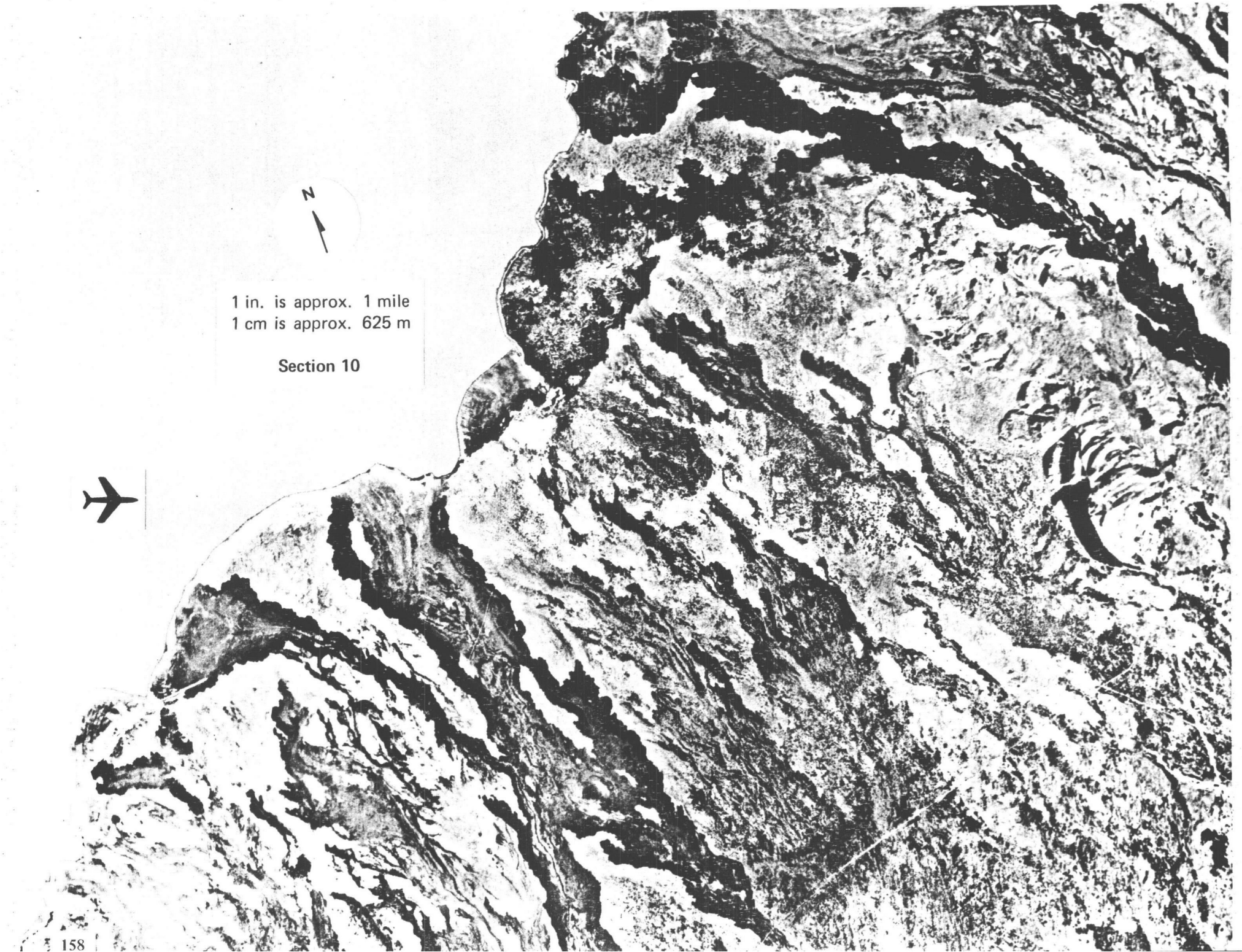
Fig. 7-62. View to the north-northwest across Mokuaweoweo; prehistoric flows in the foreground are cut by a fault that trends north and merges with the north end of the caldera. West flank of Mauna Kea is near the horizon at the right edge. Haleakala, on the island of Maui, is on the horizon above the clouds. (*U.S. Navy photography, 1954.*)

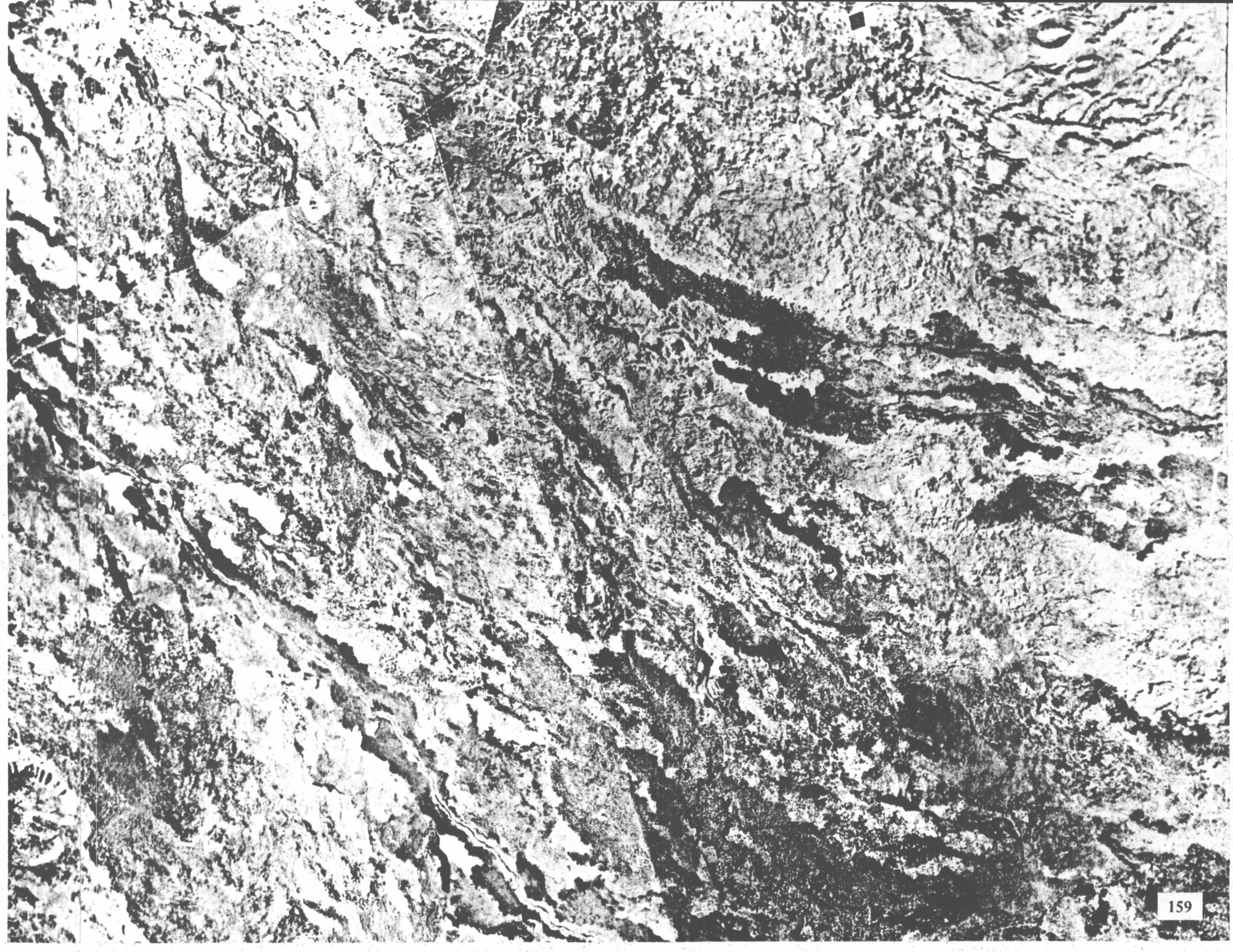
LAVA FLOW OF 1859
Halelaau
Kilauea Iki
Kilauea Crater
Halemaumau
Kilauea Caldera
Kilauea Volcano
Kilauea Iki Crater
Halemaumau Crater
Kilauea Caldera
Kilauea Volcano
Kilauea Iki Crater
Halemaumau Crater

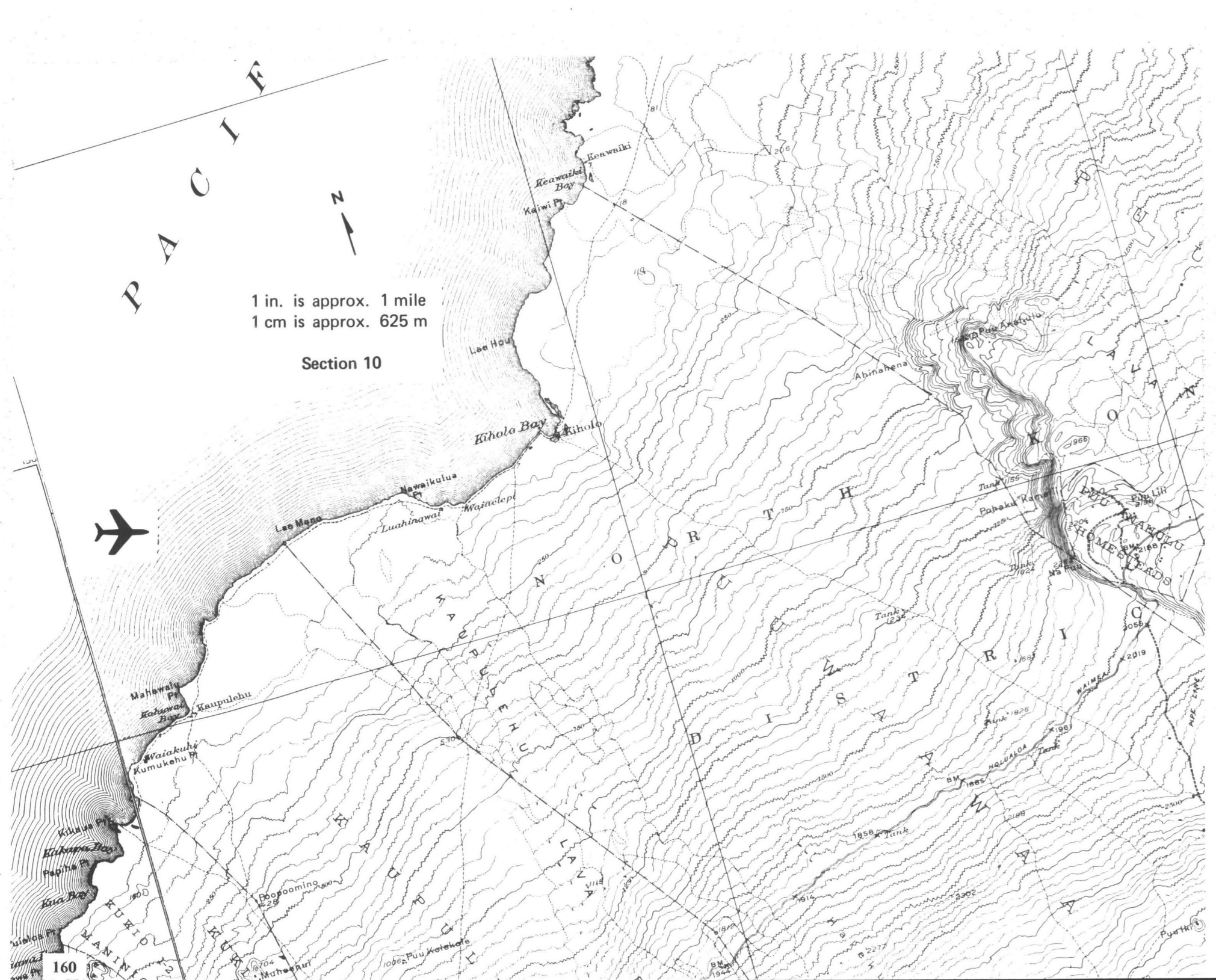

N
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 8
155


MANINIOWALI
AWAKEE
Lava Flow of 1801
MAHAILUA
KAULANA
KAMAKAOA
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 9

Haloisau
Puu Kaanui
Puu Kaanui
Puu Kaanui


N
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 10




PACIFIC
N
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 10
Keawaiki
Keawaiki Bay
Kaiwi Pt
Lae Hau
Kiholo Bay
Kiholo
Nawaikulua Pt
Waiawlepi
Luahinawai
Lae Mano
Mahawahi Pt
Kahuwai Bay
Kaupulehu
Waiakuhi
Kumukehu Pt
Kikaua Pt
Kukuna Bay
Papiha Pt
Kua Bay
Poopoomino
Puu Kaleleole
Muheehue
Abinahena
Puu Anaulu
Pohaku Kani
Puu Lili
Tank 1155
Tank 1234
Tank 1826
Tank 1958
Tank 1944
Tank 1965
Tank 1924
Tank 2277
BM 1665
BM 2188
Na Puu
HOMESTEADS
KAHUKU
KAUPULEHU
KAHUKU
KAUPULEHU
KAHUKU
KAUPULEHU

161
Kipuka Kiolakaa
Kipuka Kiolakaa
Kipuka Kiolakaa

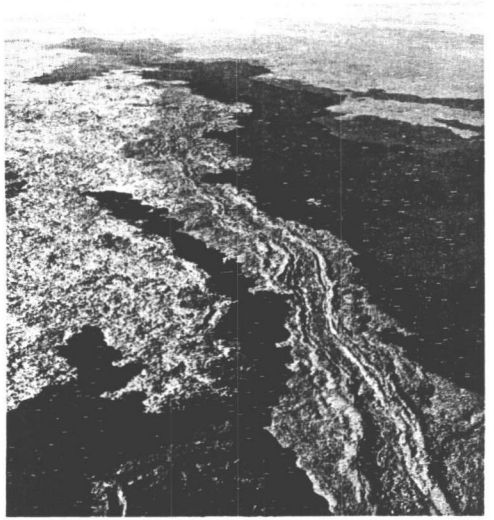


Fig. 7-63. Lava flows on the upper slopes of Mauna Loa and a typical leveed lava channel developed in an aa flow. The channel levees result from rubble that is pushed laterally during active flow within the channel. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

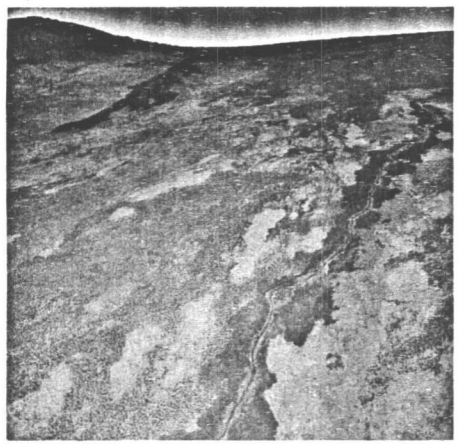


Fig. 7-64. View to the southeast toward the saddle between Mauna Kea (left) and Mauna Loa (right). Dark flows in the saddle area are from the 1750 (?) eruption. Prominent flow on the right is the 1859 flow, which originated at the 3400 m elevation on Mauna Loa and flowed more than 50 km to the sea where it formed pillow lavas. The eruption lasted 7 months, extruding 310×10^6 m^3 of lava. (*U.S. Navy photograph, 1954.*)

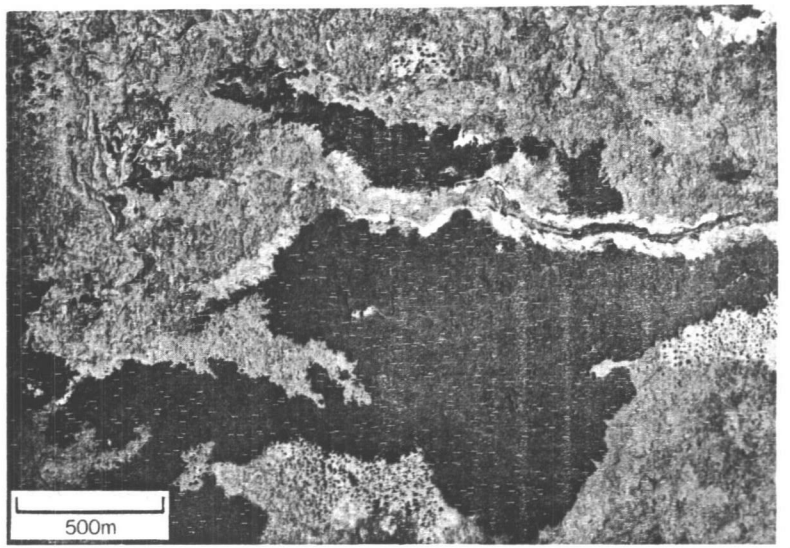


Fig. 7-65. Vertical aerial photograph of the main lava channel of the 1859 flow from Mauna Loa (flow direction is to the right). The channel is nearly continuous for more than 30 km (north is to the right). (*U.S. Dept. of Agriculture photograph, EKL-9CC-115, 1965.*)

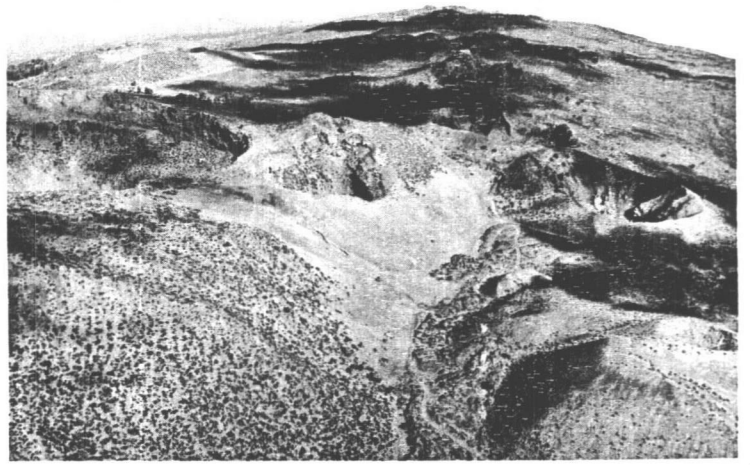


Fig. 7-66. View of the summit region of Hualalai Volcano showing numerous cinder and spatter cones. (*U.S. Geological Survey-Hawaiian Volcano Observatory photograph by John Lockwood, 1974.*)

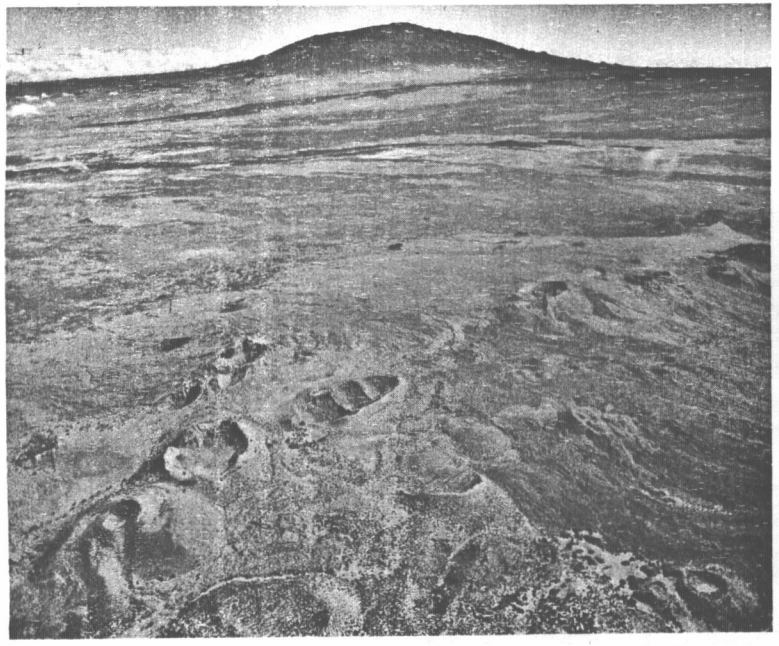


Fig. 7-67. View eastward toward Mauna Kea across prehistoric pyroclastic cones of the southeast rift zone of Hualalai. (*U.S. Navy photograph, 1954.*)

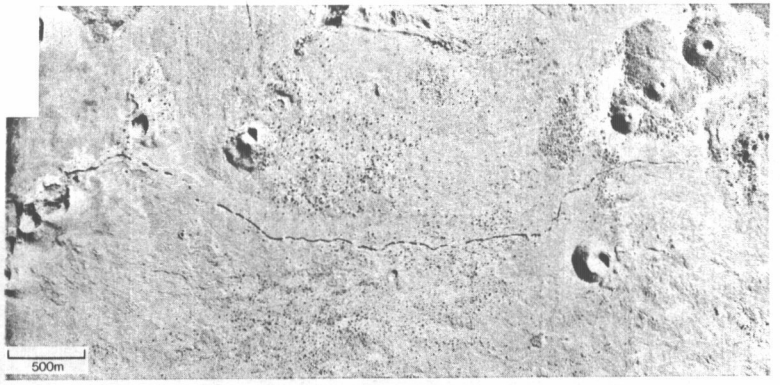


Fig. 7-69. Vertical photograph of the southeast rift zone of Hualalai (zone is traced through the pyroclastic cones on the left). Note the lava channel-lava tube that originated in flows from the pyroclastic cone and trended east about 5 km (north is to the right). (*U.S. Dept. of Agriculture photograph, 1965.*)

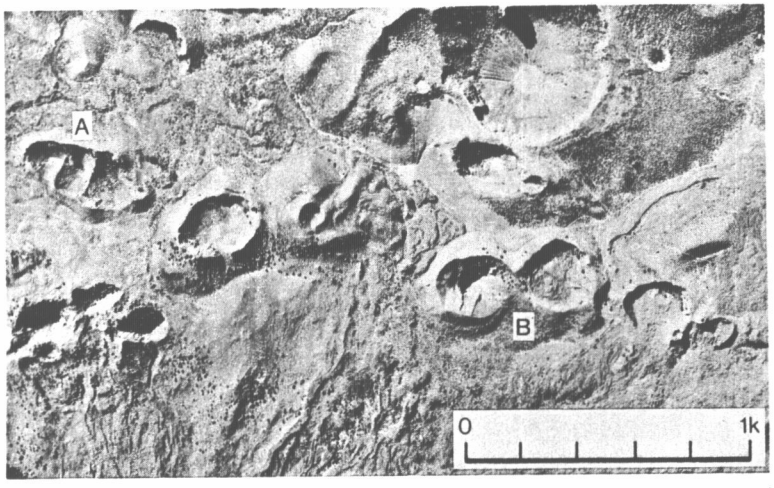


Fig. 7-68. Vertical photograph of part of the southeast rift zone of Hualalai showing the morphology of several pyroclastic cones. "A" and "B" may represent chains of vents that erupted simultaneously (east is to the left). (*U.S. Dept. of Agriculture photograph, EKL-5CC-99, 1965.*)

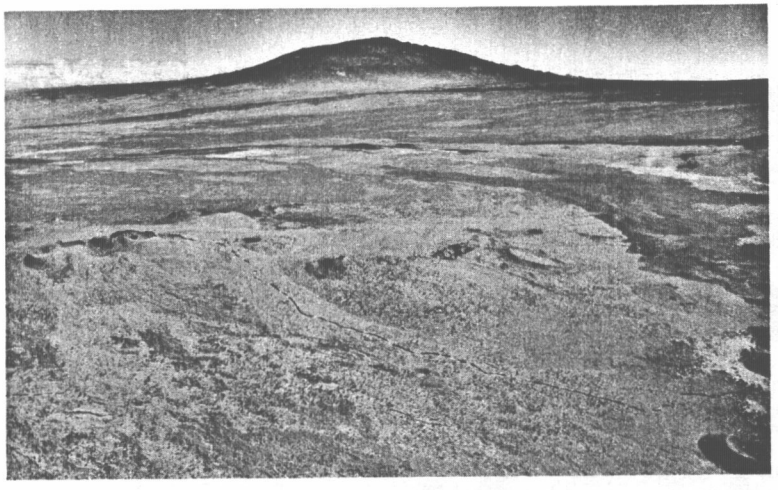
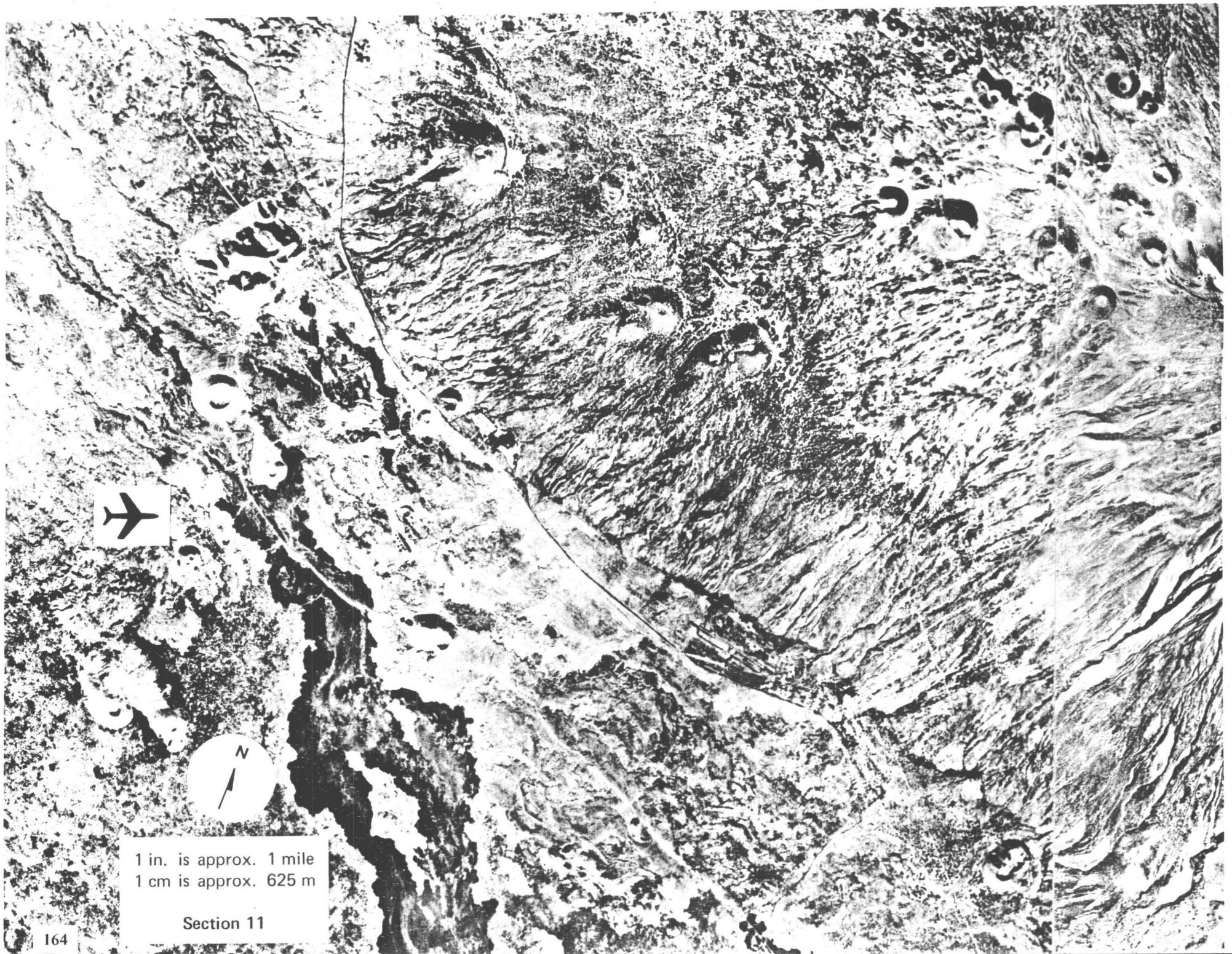
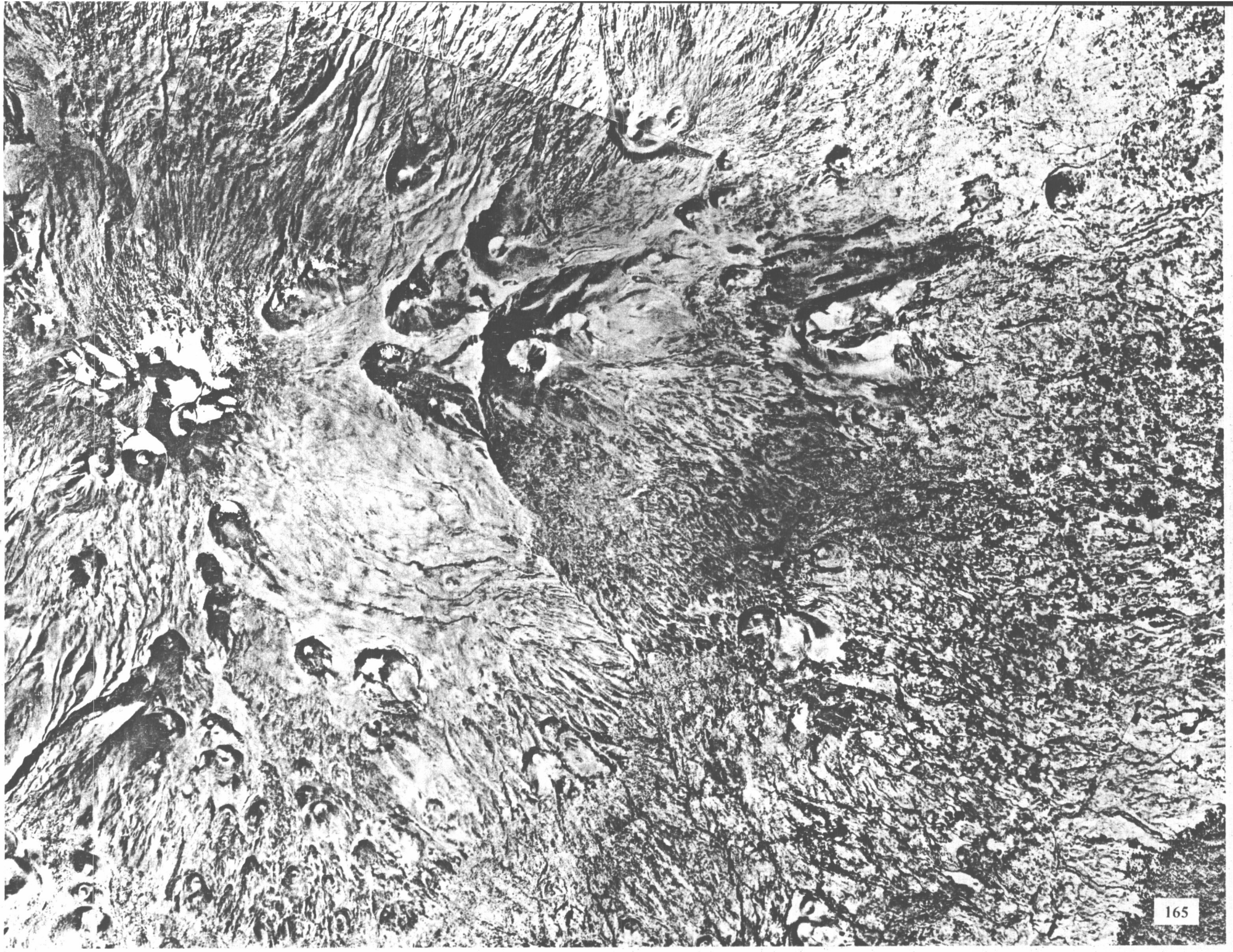
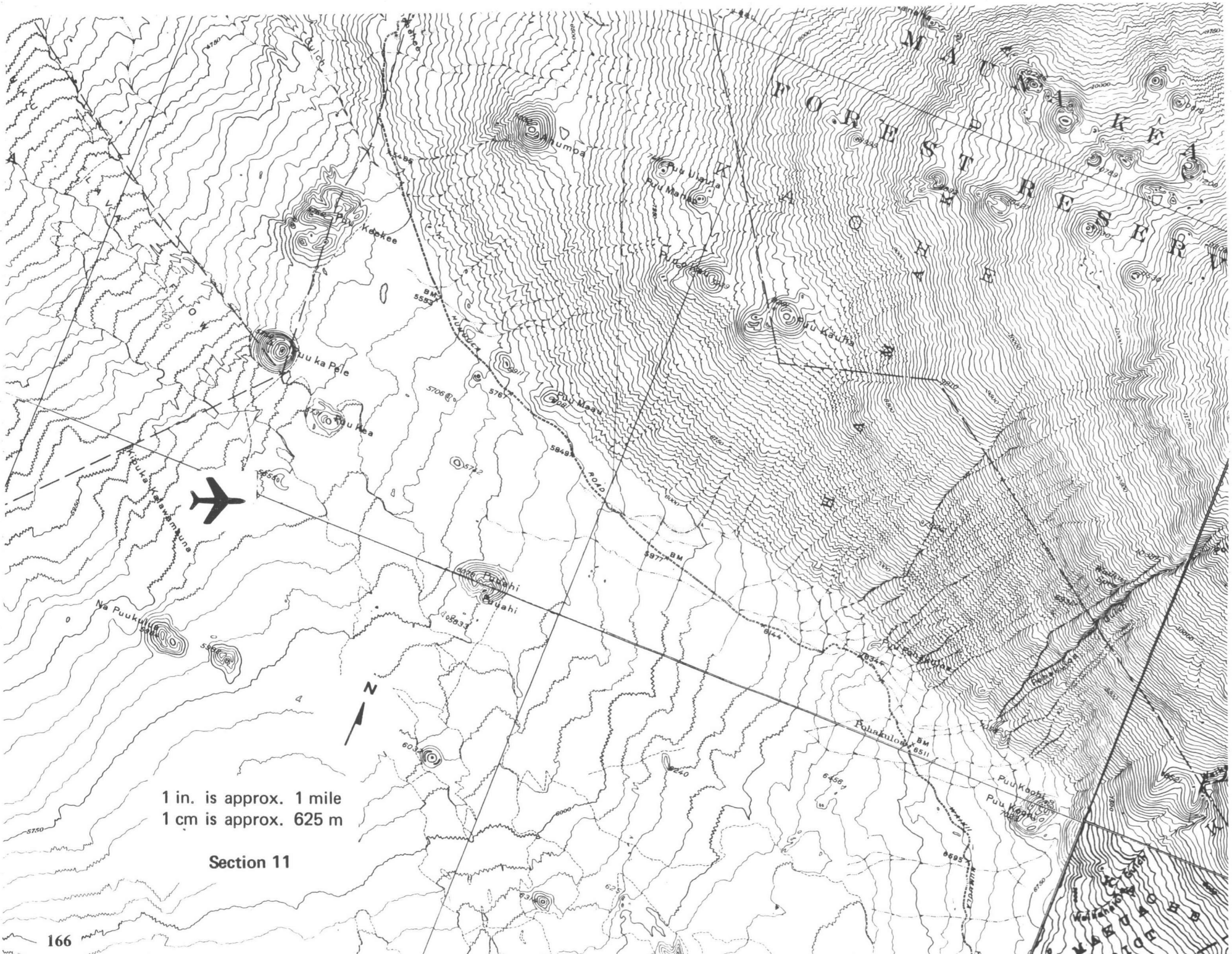
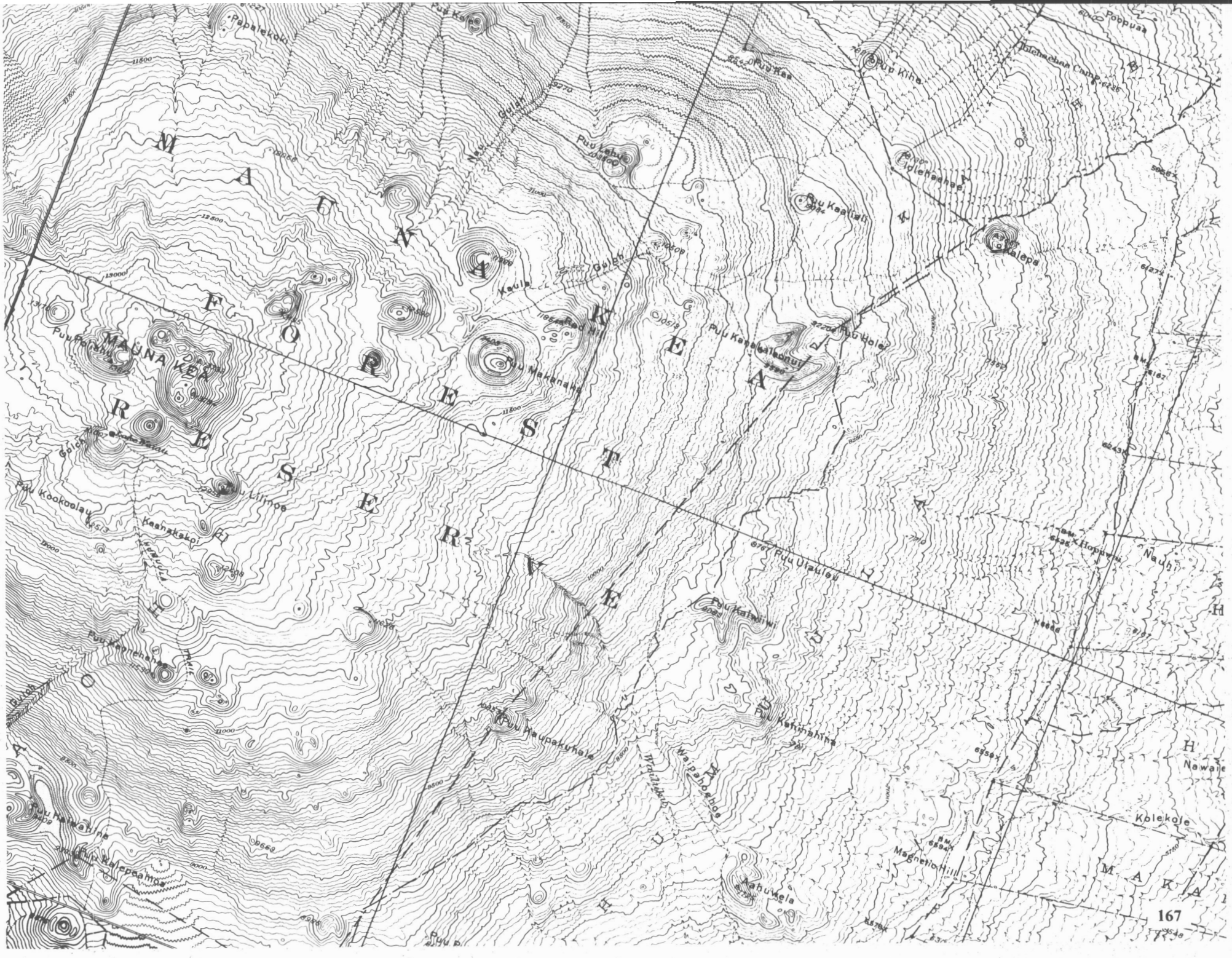


Fig. 7-70. View east-northeast toward Mauna Kea across the southeast rift zone of Hualalai. (*U.S. Navy photograph, 1954.*)


N
1 in. is approx. 1 mile
1 cm is approx. 625 m
Section 11




MAUNA KEA FOREST RESERVE
Puu Kukuhu
Puu Kea
Puu Mau
Puu Kauha
Puu Kahi
Puu Kookoo
Puu Kookoo
Puu Kookoo


MAUNA KEA FOREST RESERVE
MAUNA KEA
Papalekaki
Puu Kea
Puu Kihe
Poopuaa
Puu Kaa
Puu Kahe
Puu Kaa(tail)
Puu Kaa(tail)
Puu Hoole
Puu Makanaha
Puu Ulaulau
Puu Kookoolau
Puu Ulinipe
Puu Kaohelehele
Puu Kaohelehele
Puu Kalepeahina
Puu Kalepeahina
Puu Kahuwela
Puu Kahuwela
Puu Kalepa
Puu Kalepa
Puu Kaluaiwi
Puu Kaluaiwi
Puu Kahinahina
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Waipahoehoe
Waipahoehoe
Waipahoehoe

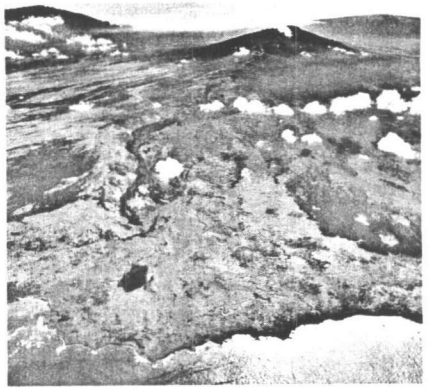


Fig. 7-71. View eastward across the Kona coast toward Mauna Kea (left), Hualalai (center), and Mauna Loa (right). Light-colored flow, left center extending into sea as a scalloped delta, is the Huehue lava flow of 1801, the last lava flow from Hualalai. Width of the delta is about 4.5 km. (*U.S. Navy photograph, 1954.*)

Fig. 7-72. View westward toward Hualalai shield volcano across the Humuula Saddle between Mauna Loa (left) and Mauna Kea (right). Dark lava flow in the center is the 1935 flow from Mauna Loa. (*U.S. Navy photograph, 1954.*)

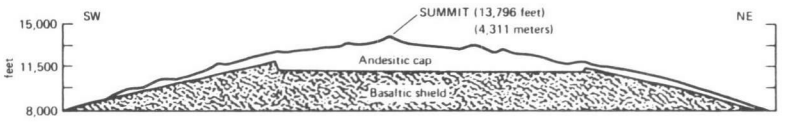


Fig. 7-73. Cross section of Mauna Kea, showing the hypothetical caldera buried beneath the cap of andesitic lavas (*from Stearns and Macdonald, 1946*).

Fig. 7-74. Looking westward toward the summit of Mauna Kea. Lava has issued from the flank of the cinder cone in the foreground and spread out fanwise. A similar fan of lava issued from the base of Summit Cone in the distance (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

Fig. 7-75. View northeastward across cinder cones at the summit of Mauna Kea. In order from foreground are Lake Waiau at altitude 3968 m (highest elevation lake in United States, A. Abbott, pers. commun.), Goodrich Cone, Summit Cone and the astronomical observatories of the University of Hawaii, and Puu Makanaka in the right foreground. Lake Waiau is contained in Puu Waiau, which is predominantly hyaloclastite and resulted from a subglacial eruption (S. Porter, pers. commun.). (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

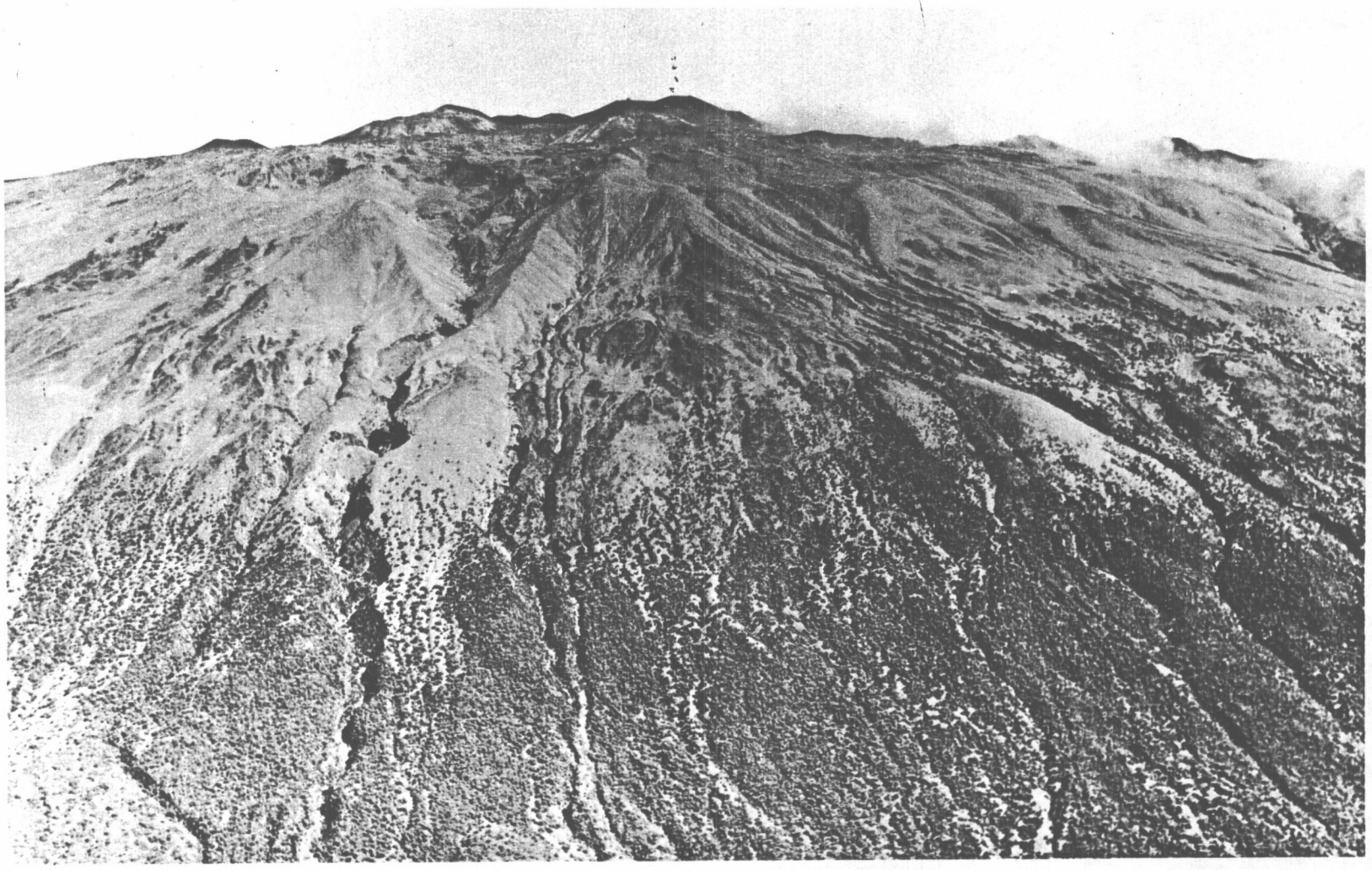
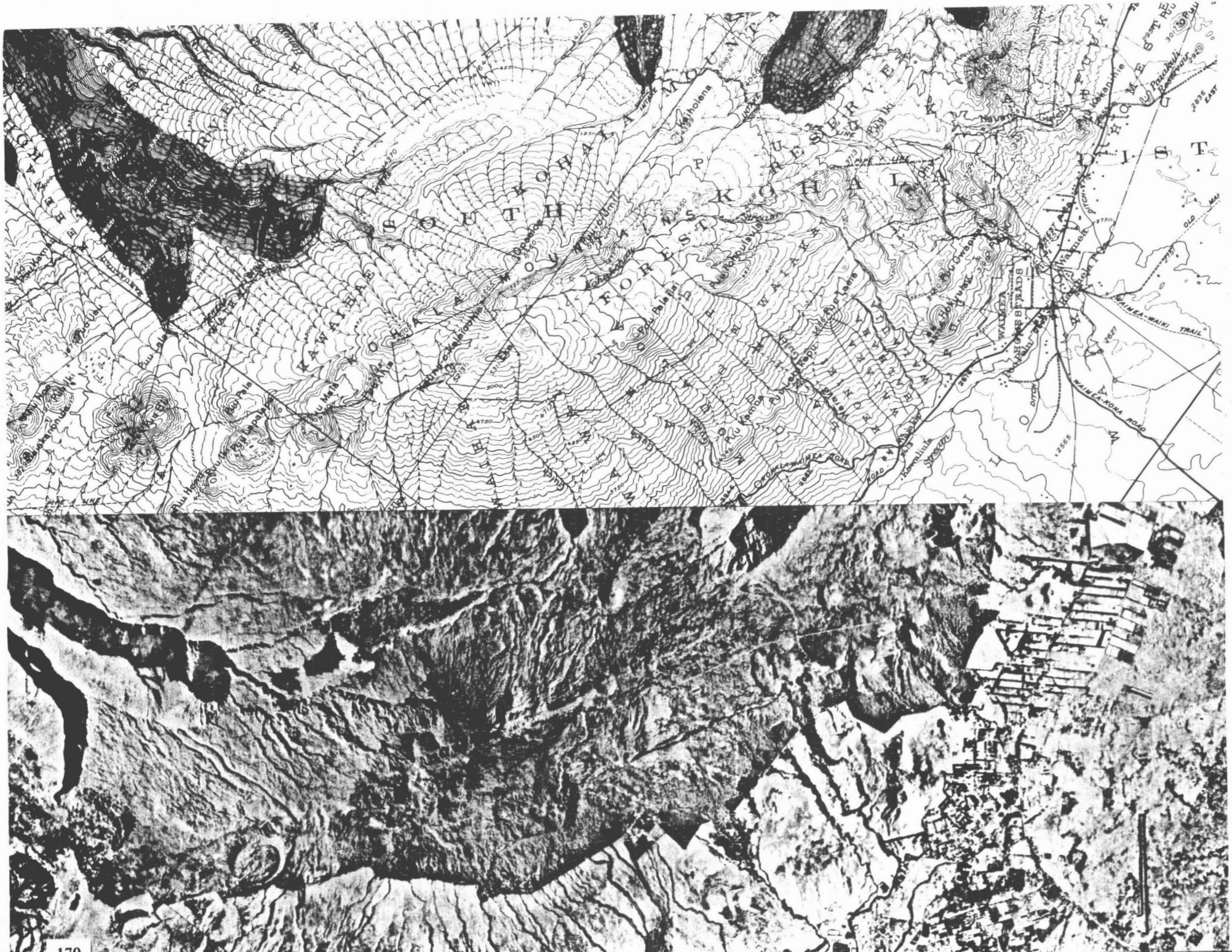
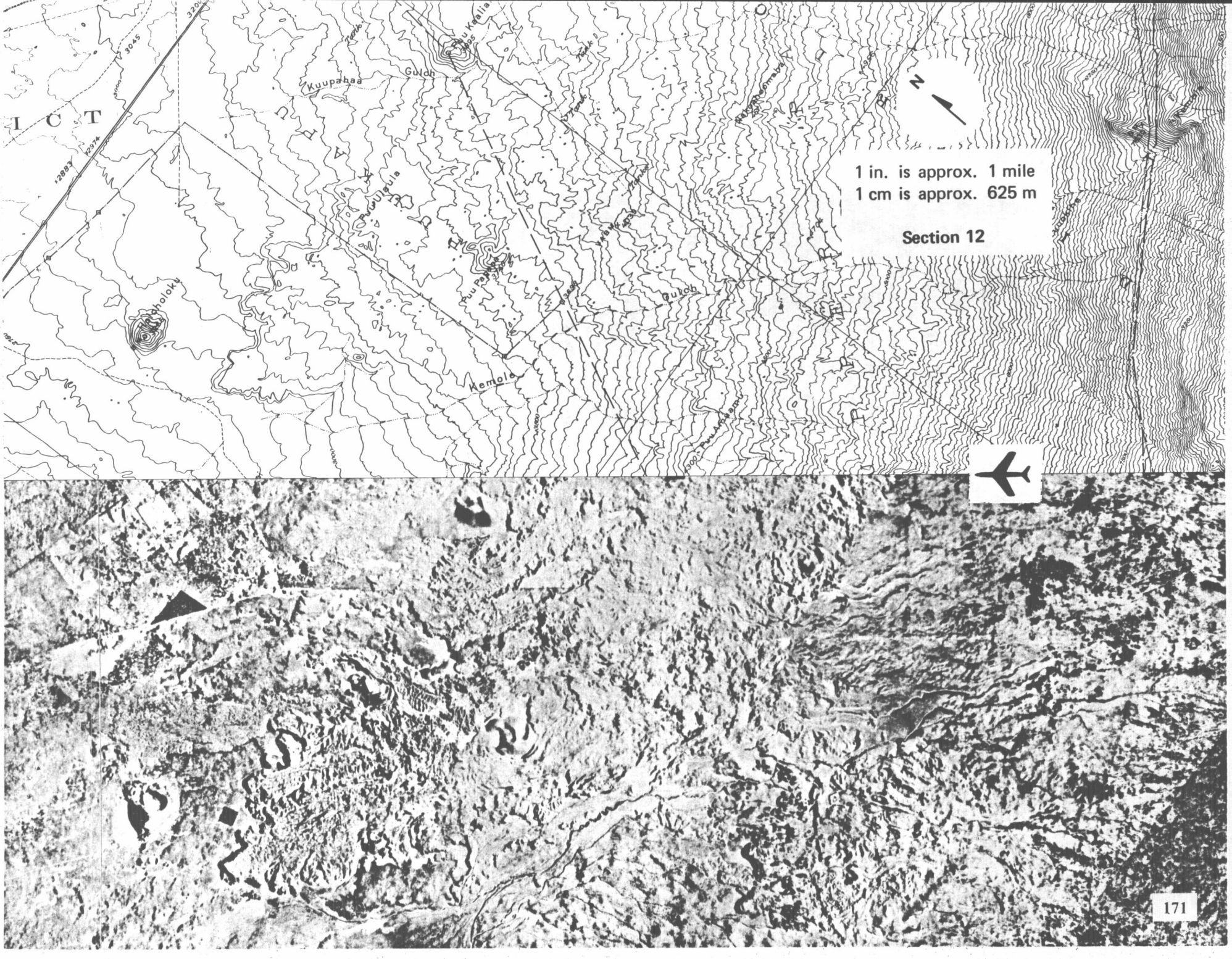


Fig. 7-76. The summit and south flank of Mauna Kea showing glacial terminal moraine. Near the center is a V-shaped loop of moraine left by the Pohakuloa lobe of the glacier. From it the main moraine ridge extends both to the left and the right. Below the Pohakuloa loop the prominent gorge of Pohakuloa stream was excavated primarily by melt water from the lobe of the glacier (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).


SOUTH KOHALA MOUNTAINS
KAWAIHAE
SOUTH KOHALA FOREST RESERVE
KOHALA
WAIMEA
WAIKOLOA
Puu Kapuaiwa
Puu Mala
Puu Hinai
Puu Kaiholena
Puu Kalaiki
Puu Kawaiwai
Puu Kaiwi
Puu Kaumaka
Puu Kaiholena
Puu Kaiwi
Puu Kawaiwai
Puu Kaumaka
Puu Kalaiki
Puu Kapuaiwa
Puu Mala
Puu Hinai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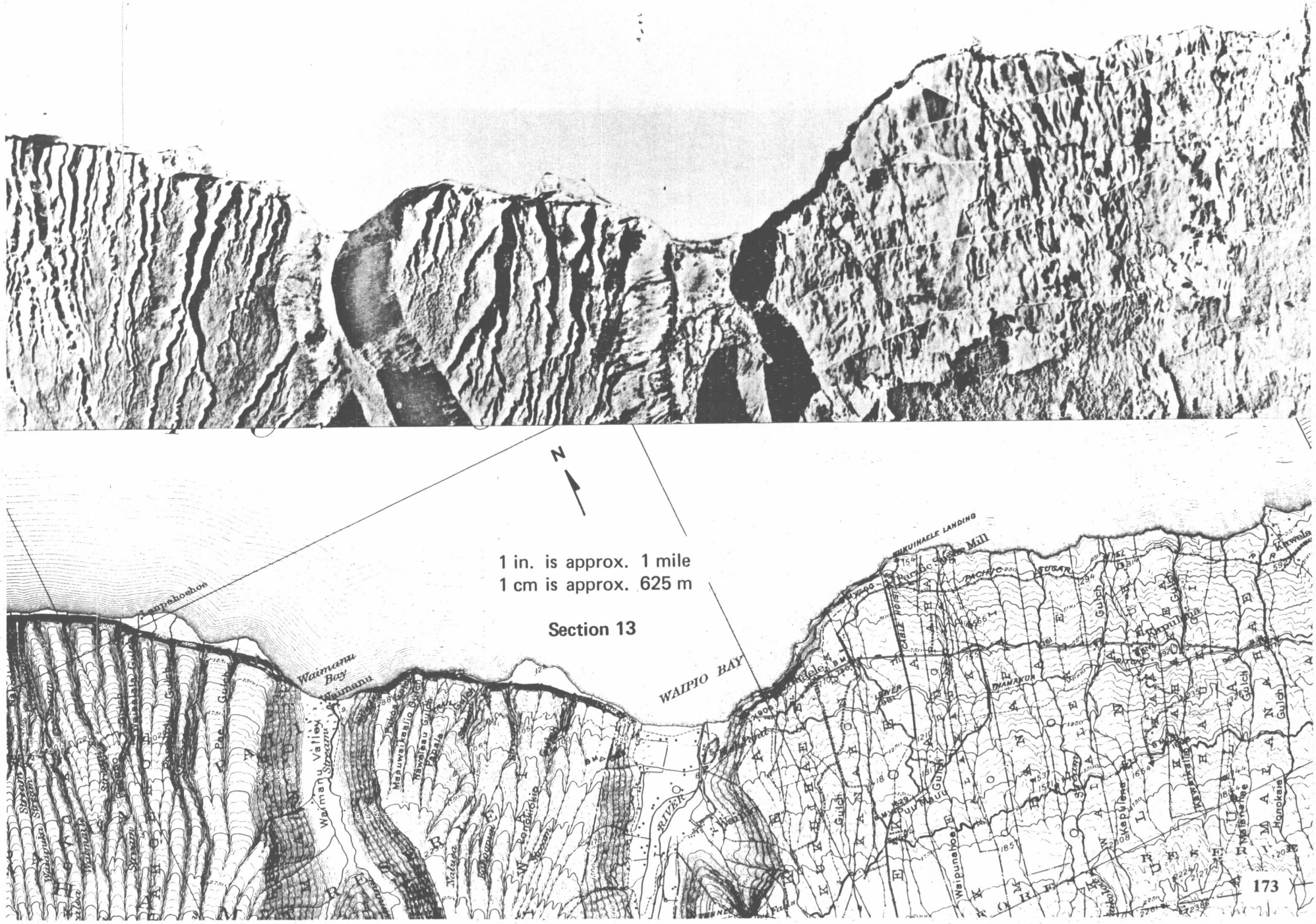
Section 12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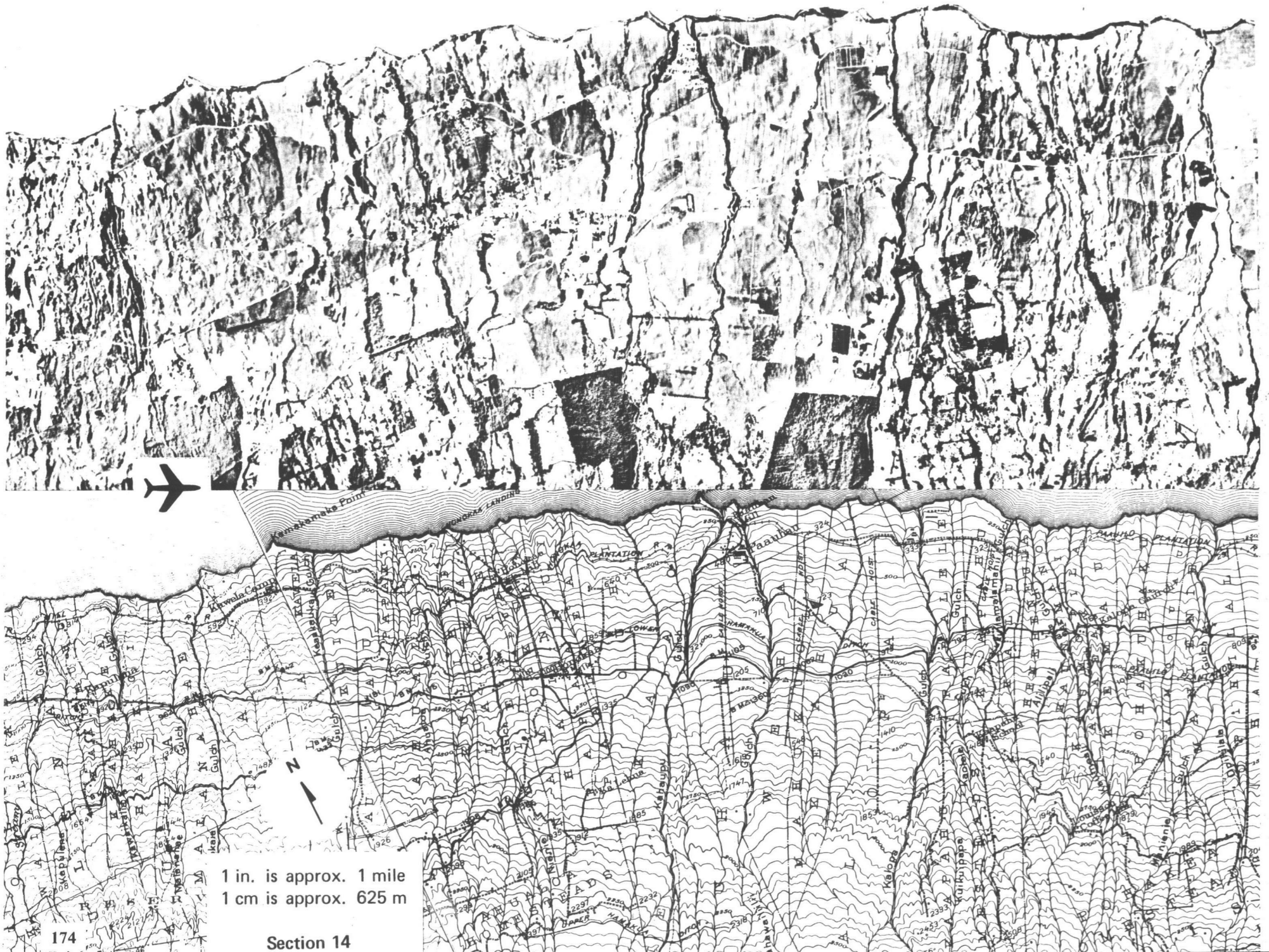
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Kaeleulu Gulch
Kahaupu Gulch
Kahaupu Ridge
Kaholo Gulch
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Kaholo Trail
Kaholo Plantation
Pahuhui
Pahuhui Gulch
Pahuhui Plantation
Kaholo Cliffs
Kaholo Peak
Kaholo Plantation
Kaholo Gulch
Kaholo Ridge
Kaholo Trail

175
HONOLULU
KAHOAMOKU
KAIMUKI
KAPIOLANI
KEALAKEKUA
KEAWAIWI
KOOLAU
KUPEPAUILA
MAKIKI
MANOA
NUUANU
PALOLO
PUNCHBOWL
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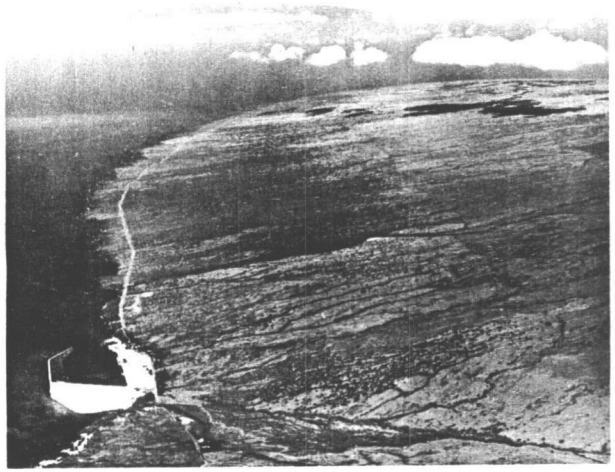


Fig. 7-77. Northwestern slope (leeward side) of Kohala volcano, showing relatively little erosional dissection on this drier and younger side of the mountain in contrast to that on the wet northeastern side (Fig. 7-78). The port of Kawaihae lies in the foreground, and the summit of Haleakala, on Maui, rises on the horizon above the clouds (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

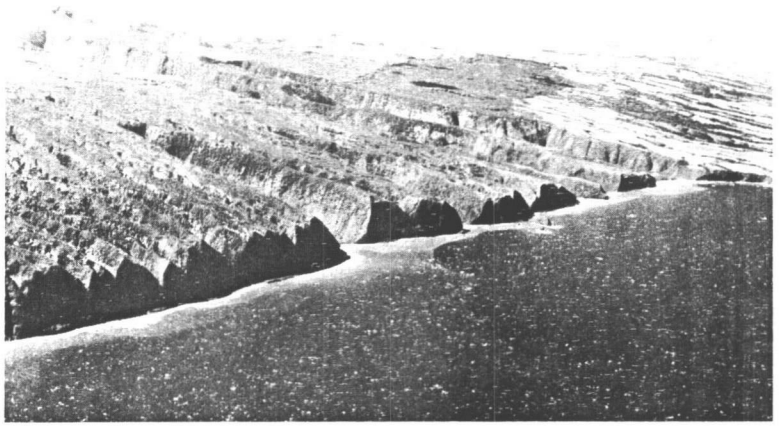


Fig. 7-78. Sea cliff cut across lavas of the Pololu Volcanic Series on the northeastern side of Kohala volcano. The straight line of cliffs resembles faceted spurs resulting from faulting; however, the morphology is apparently the result entirely by erosion. The floors of the major valleys are close to sea level, but the smaller valleys are "hanging" and their streams enter the ocean as waterfalls (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

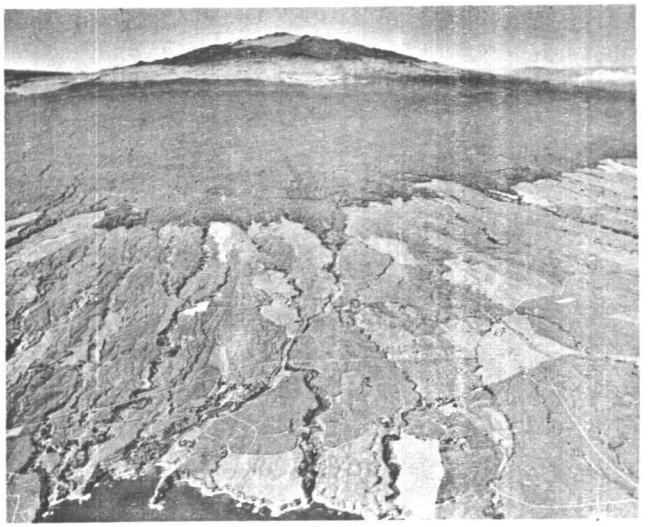


Fig. 7-79. View westward across the Hamakua Coast toward Mauna Kea volcano. High rainfall on this, the windward side of the island, combines with the rich soils of the Pahala ash to produce abundant sugar cane crops. (*U.S. Navy photograph, 1954.*)

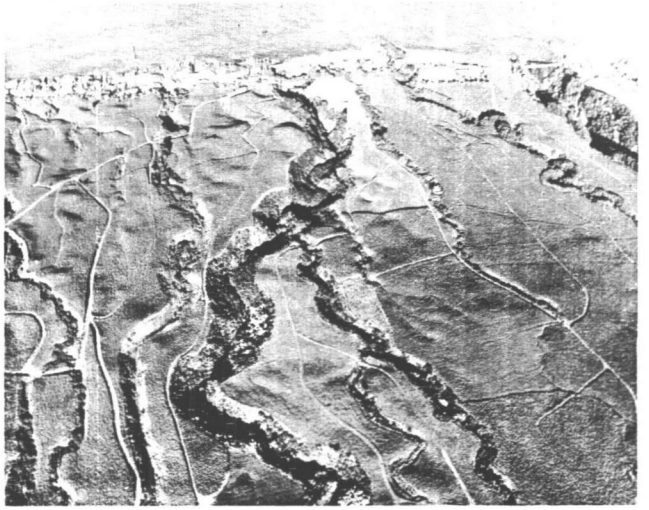


Fig. 7-80. Youthful valleys of consequent streams on the Hamakua Coast. The narrow V-shaped valleys are separated by broad areas, covered with a blanket of ash, that are almost untouched by erosion. The "ghost" of an earlier lava flow topography can be seen through the ash (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

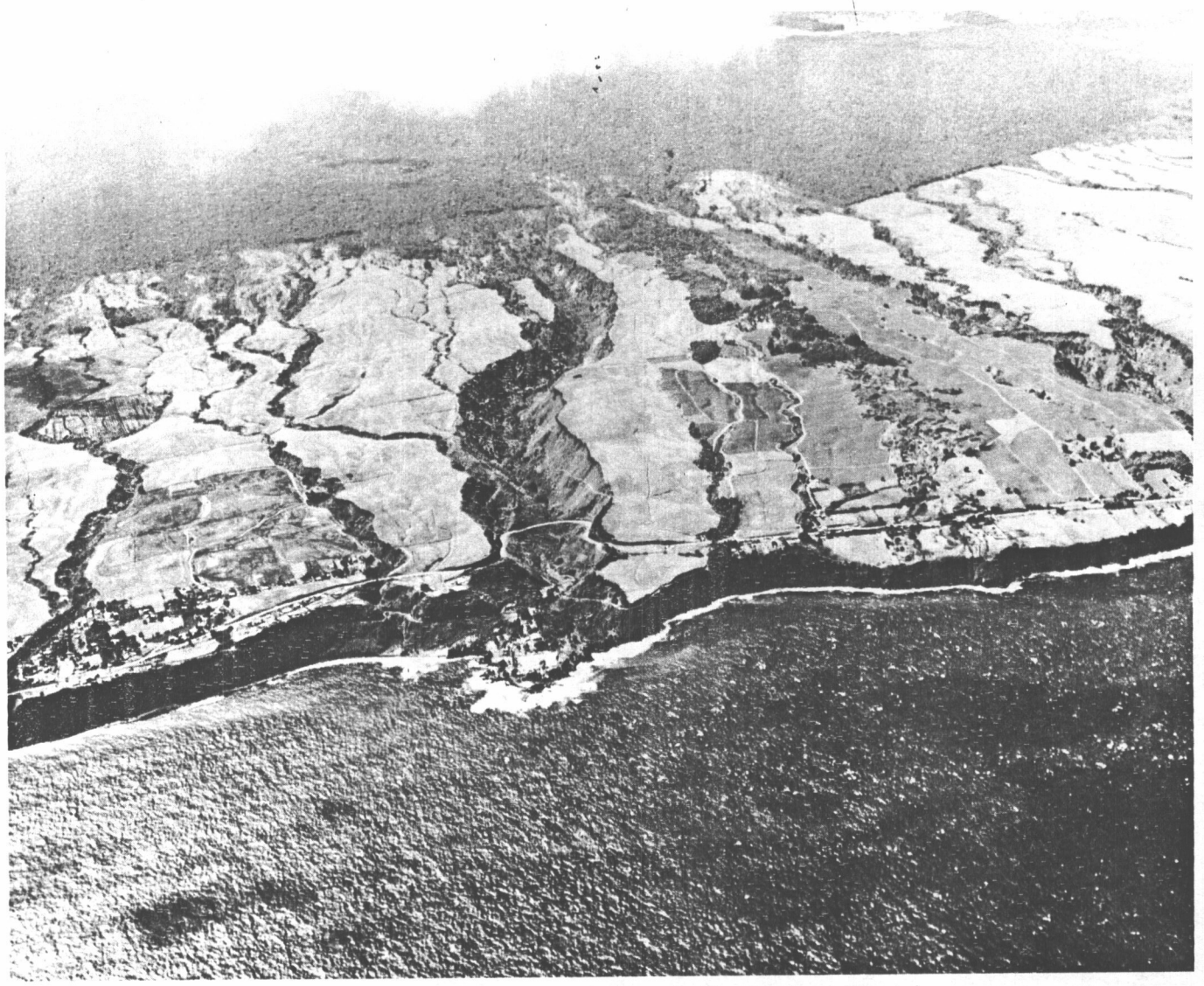
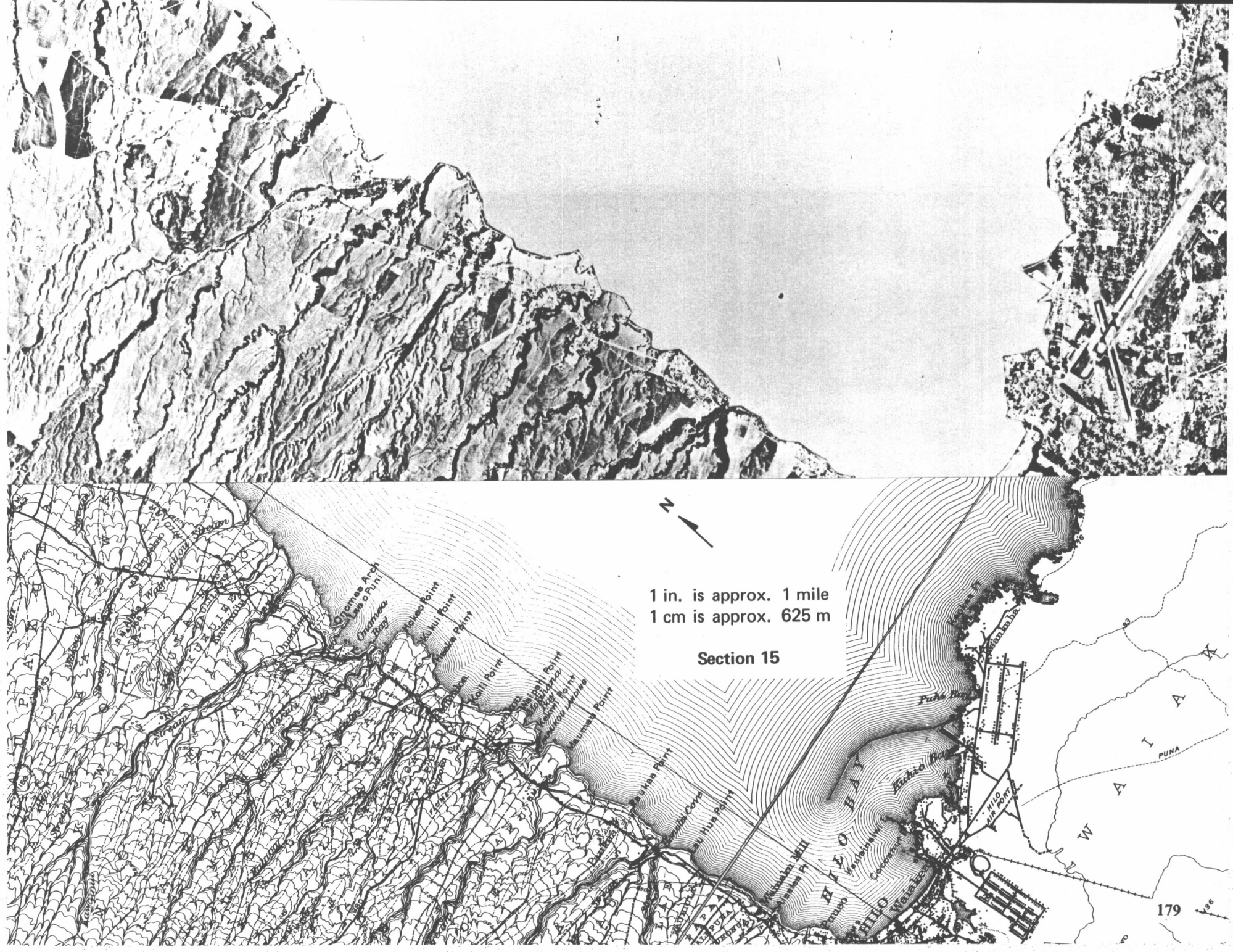


Fig. 7-81. Laupahoehoe gulch and peninsula on the Hamakua Coast. The peninsula was formed by a late lava flow that descended the valley. The topography is very youthful. Note the "slipover" of capture consequent streams as they enter the main valley on the left side. At Laupahoehoe Point, in the foreground, 26 persons were killed during the tsunami of April 1, 1946 (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

INTERIOR
SURVEY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Section 15
Onomea Arch
Leo o Puini
Onomea Bay
Kolekeo Point
Kahuli Point
Hawea Point
Kalili Point
Punahoa Point
Kaumaka Point
Kaumaka Point
Kaumaka

Fig. 7-82. Looking southward across Hilo Bay and Hilo. The tsunami of April 1, 1946, destroyed a substantial part of the breakwater, and water heights above 7 m (measured above the normal shoreline) devastated many of the buildings along the waterfront. The tsunami of May 23, 1960, similarly flooded much of downtown Hilo. (*U.S. Navy photograph, 1954.*)

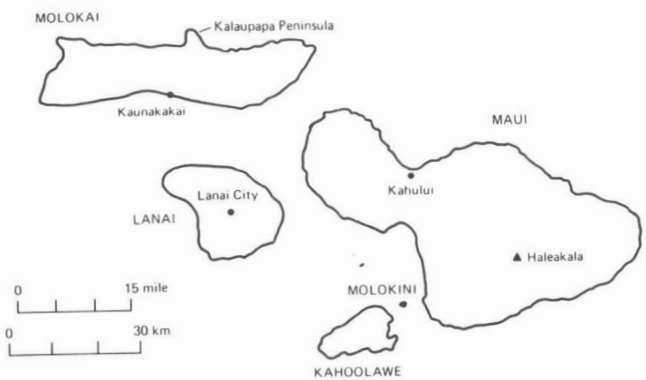

Fig. 7-83. Map of the islands of Maui, Kahoolawe, Molokini, Lanai, and Molokai, showing areas illustrated in the figures that follow.

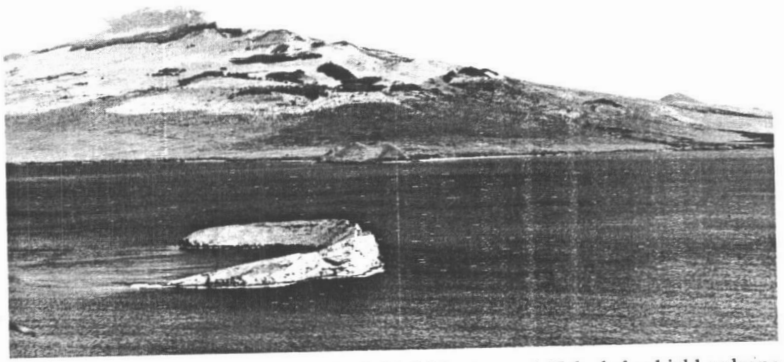

Fig. 7-84. View eastward across Molokini islet toward Haleakala shield volcano on the island of Maui. Cinder cones on the horizon extending from the summit to the right mark the southwest rift zone of Haleakala. Molokini islet is a cone of palagonite tuff formed by eruption in the ocean. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

Fig. 7-85. View down the southwest rift zone of Haleakala from the summit toward Kahoolawe Island, on line with the rift. Cinder cones are part of the Pleistocene Kula, and Holocene Hana Volcanic Series. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

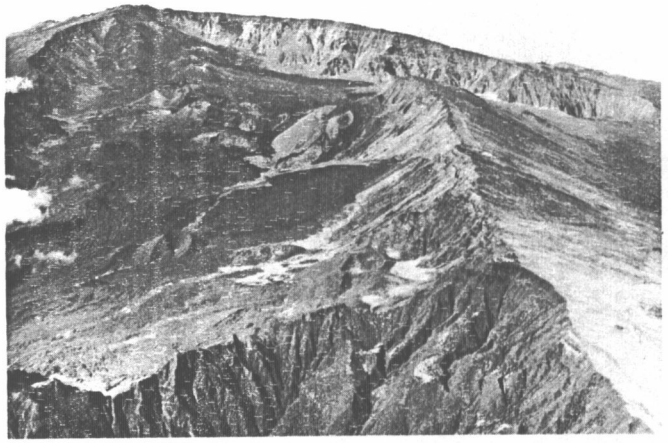

Fig. 7-86. View of Haleakala Crater looking southwestward along the rift zone showing the continuity of the rift inside the crater, marked by cinder cones. Kaupo Gap is on the lower left and Koolau Gap on the right (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

Fig. 7-87. View across the erosional summit crater of Haleakala and cinder cones on the crater floor. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

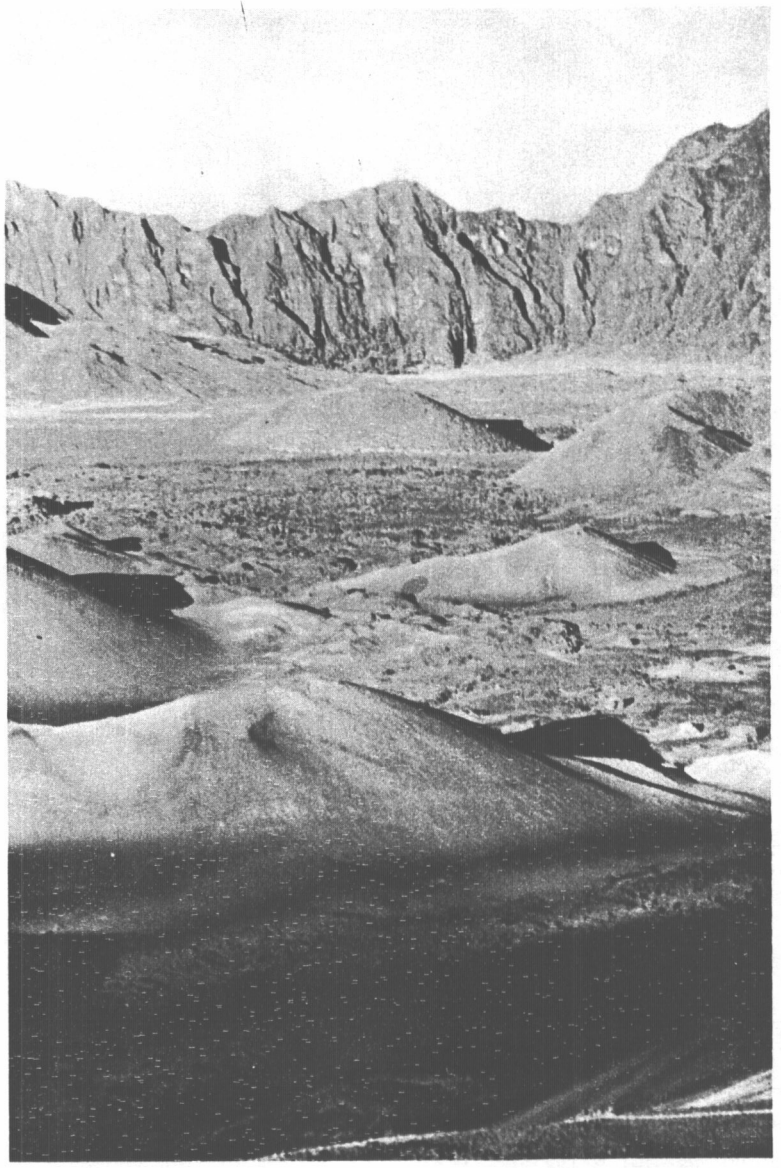

Fig. 7-88. View across Haleakala summit caldera from the observation shelter on the summit. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

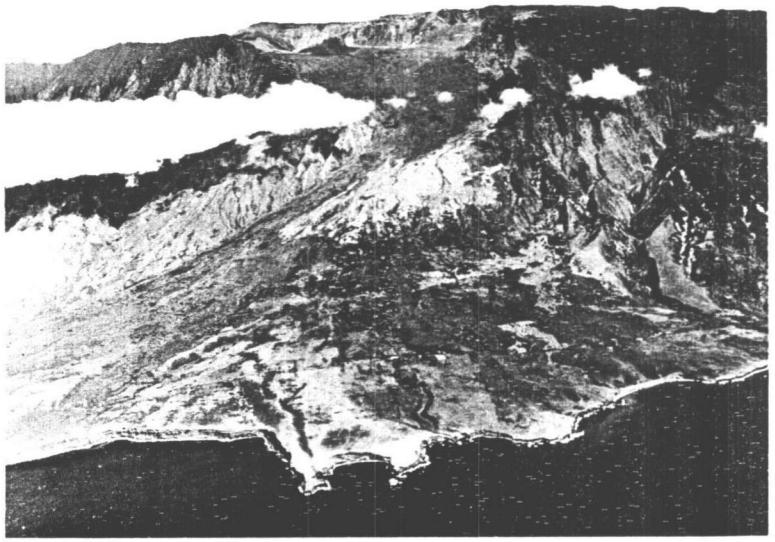

Fig. 7-89. Kaupo Gap, Haleakala Volcano, East Maui. Lava flows of the Hana Volcanic series poured seaward through an erosional valley that formed during a long period of volcanic inactivity. Mudflows containing huge jumbled blocks are associated with these lava flows. Manawainui Valley is on the right (*from Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott*).

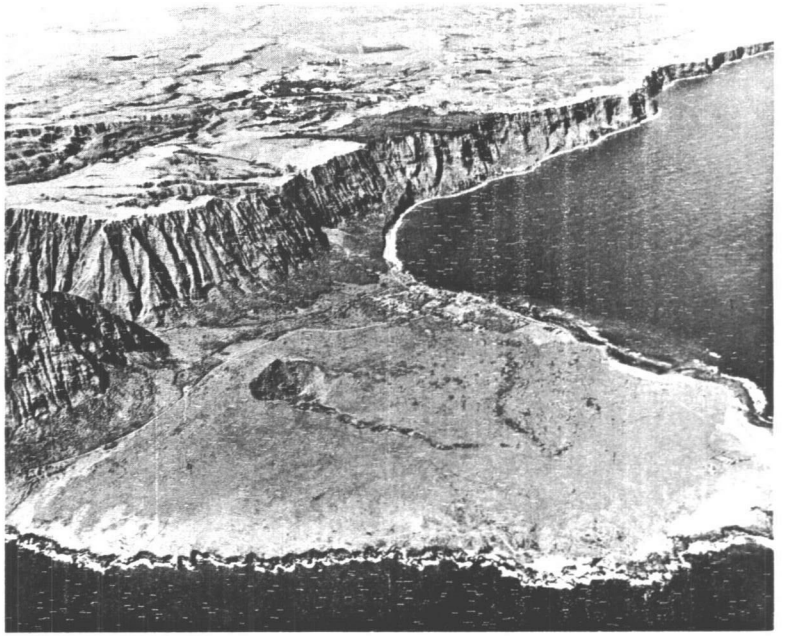

Fig. 7-90. View southwestward across Kalaupapa peninsula, a small shield volcano built of Quaternary olivine basalts, mostly pahoehoe. A collapsed lava tube extends northward from the summit vent, Kauhako Crater. (*Hawaii Institute of Geophysics photograph by Agatin T. Abbott.*)

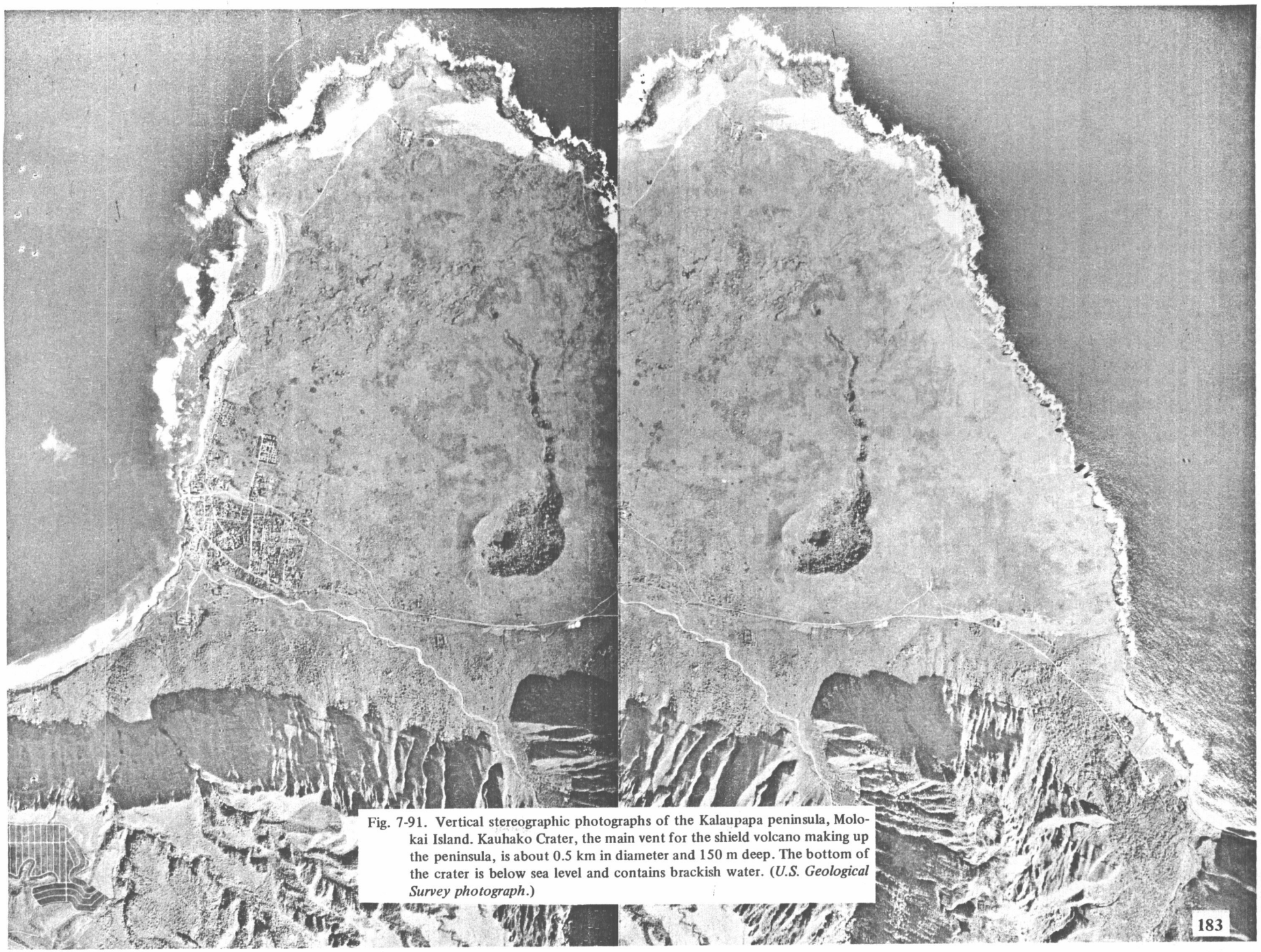

Fig. 7-91. Vertical stereographic photographs of the Kalaupapa peninsula, Molokai Island. Kauhako Crater, the main vent for the shield volcano making up the peninsula, is about 0.5 km in diameter and 150 m deep. The bottom of the crater is below sea level and contains brackish water. (*U.S. Geological Survey photograph.*)

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8. ROAD GUIDE TO GEOLOGICAL POINTS OF INTEREST ON THE ISLAND OF HAWAII

Reprinted from Stearns, H. T. and Macdonald, G. A., 1946. Geology and ground water resources of the island of Hawaii, Hawaii Div. Hydrography Bull. 9, Plate 1.

With minor additions by
Ronald Greeley
University of Santa Clara
Santa Clara, California 95053

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This road guide briefly describes the points of geologic interest along the main roads on Hawaii. It begins at Hilo (Fig. 8-1) and proceeds around the island in a clockwise direction on State Route 11 to Kailua, then returns to Hilo on State Route 19 to Hilo via Waimea, with side excursions on the other principal roads.

Minimum excursion time is two days, allowing only very brief time for the various stops. The return to Hilo from Waimea can be made via Route 19 along the Hamakua Coast (wet, leeward side of island, displaying typical tropical erosion) or via Route 20 over the Humuula Saddle (high, relatively dry and cool; young volcanic features).

This guide has only been minimally updated from the original publication in 1946. For the Kilauea, Ka'u Desert, and east Puna regions (sites of recent volcanic activity), the reader is referred to the separate guides.

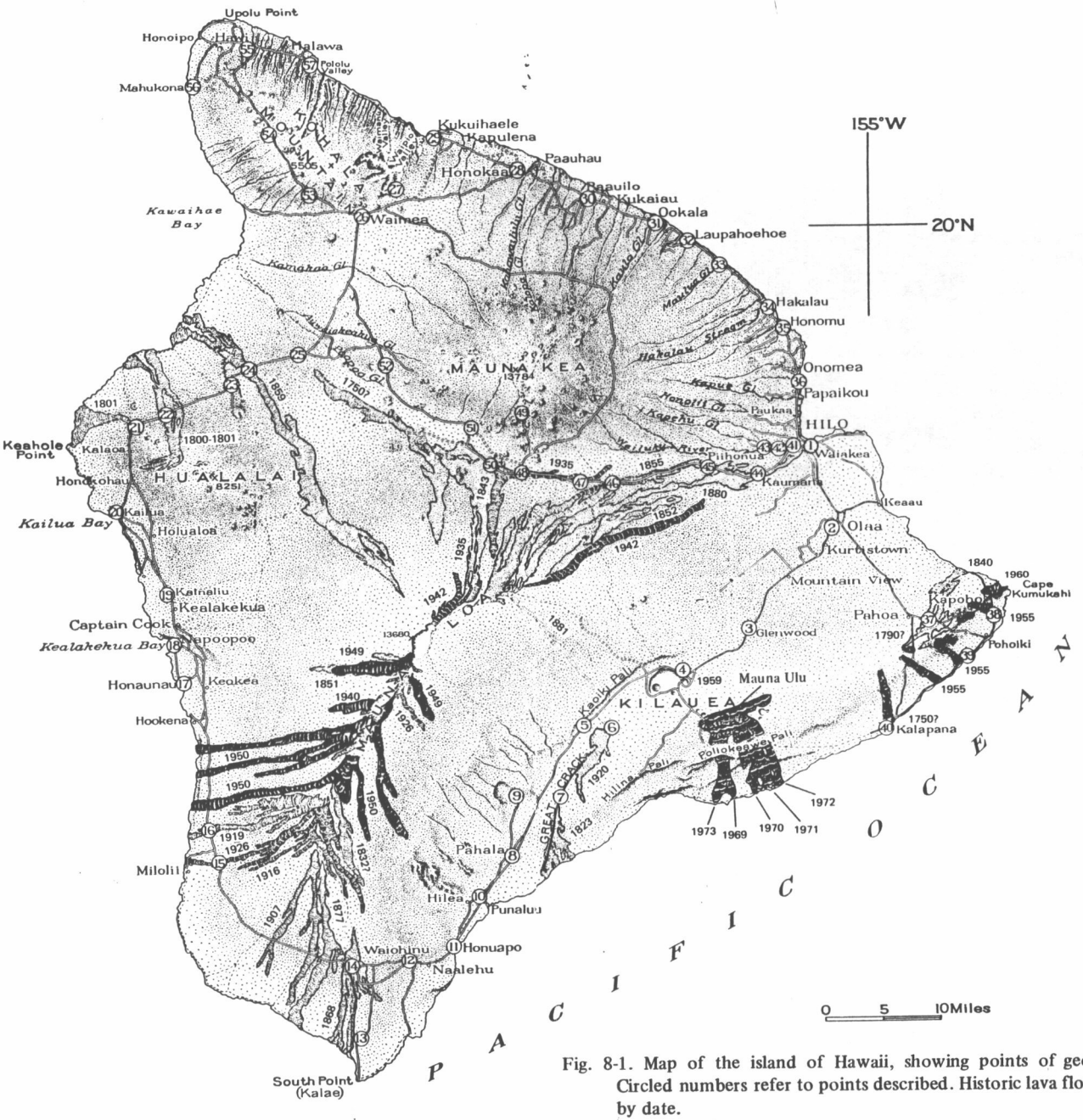

Fig. 8-1. Map of the island of Hawaii, showing points of geological interest. Circled numbers refer to points described. Historic lava flows are identified by date.

1. Waiakea Estuary. Basal springs discharge 146 million gallons a day, comparable to the largest springs in the continental United States.

Fig. 8-2. View across Waiakea Estuary toward Hilo Airport. (*NASA-Ames Research Center photograph by Mike Lovas, August 1970.*)

2. Olaa. Location of a Maui-type well where an elevator descends 67 m to the pump chamber at sea level. The water is pumped from the basal zone of saturation where fresh water floats on salt water because of its lesser specific gravity.

3. Glenwood. Road cuts expose 2.4 m of Pahala ash overlying lavas of the Kahuku volcanic series of Mauna Loa. One and a half kilometer southwest of Glenwood the highway passes from the slope of Mauna Loa to that of Kilauea. A change from Pahala ash to fresh olivine basalt with scanty ash cover indicates the boundary.

4. Hawaii National Park headquarters. For a guide to Kilauea Caldera and vicinity, see separate guide by the Hawaiian Volcano Observatory Staff.

5. The Kaoiki Pali, parallel with the road on the northwest side, is a fault scarp in lavas of the Kahuku volcanic series, partly veneered with later lavas of the Ka'u volcanic series. Kahuku lavas covered with yellow Pahala ash are exposed in small kipukas along it.

6. Mauna Iki. A trail leads from the highway to Mauna Iki, a secondary lava cone built at the source of the flow of 1920. Northwest of Mauna Iki, fossil footprints in the ash of 1790 are believed to have been made by Keoua's army, one division of which was annihilated by the explosions of 1790. Some of the ash layers contain pisolites, small mud balls formed by rain drops. Eruptions in 1971 along the southwest rift zone of Kilauea produced lavas on both sides of Mauna Iki (see separate guide to the area by Cruikshank).

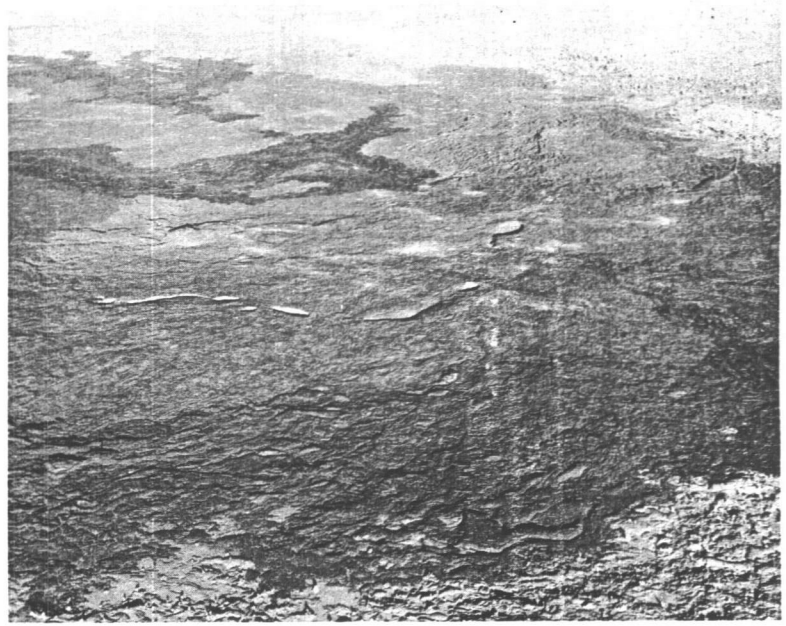

Fig. 8-3. View across pahoehoe lava flows and Mauna Iki; the 1919-20 lava tube is visible as the series of elongate collapses trending to the left from the summit. The prominent fissure cutting diagonally across the picture from the middle-right to the upper left corner is part of the southwest rift zone of Kilauea Volcano. (*Hawaiian Volcano Observatory photograph by John Lockwood, June 1974.*)

7. The Great Crack extends southwestward from Mauna Iki to the sea, nearly parallel to the highway. The lava flow of 1823 was erupted along nearly 10 km of this crack. The lava was very fluid and flowed with great rapidity, leaving a thin sheet a few centimeters to 1.5 m thick on the top of which are preserved many lava tree-molds.

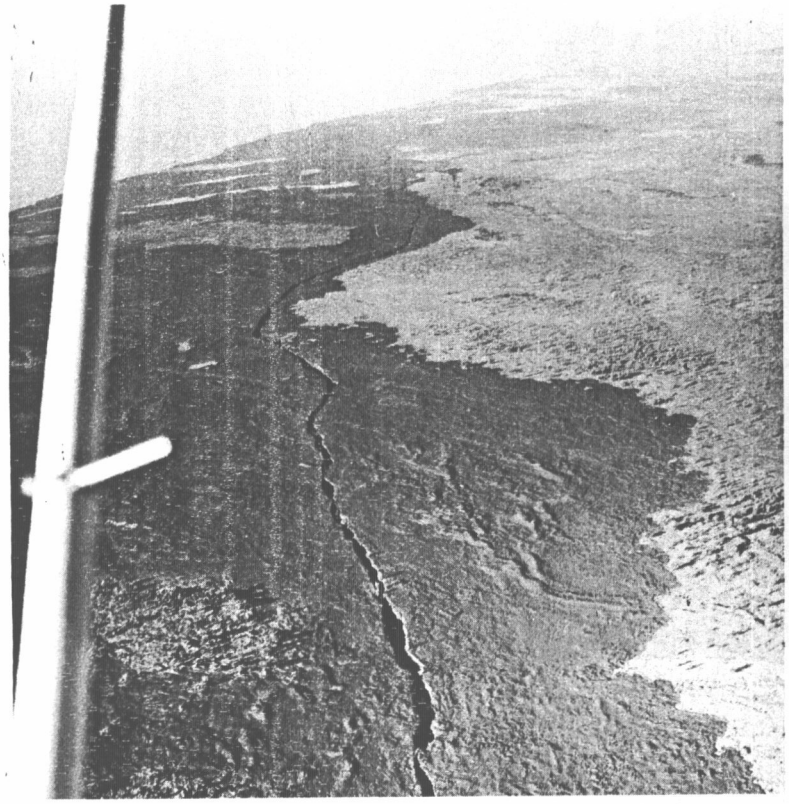

Fig. 8-4. View south southwestward down the Great Crack and the 1823 flows. *(Photograph by Ronald Greeley, University of Santa Clara, June 1974.)*

8. Pahala. This is the type locality of the Pahala ash which forms the fertile cane fields here. Numerous artificial tunnels recover water perched on ash beds in the forest above the town.

9. Wood Valley was the site of a mud flow which overwhelmed a village during the earthquakes of 1868. Soil saturated with water was shaken loose from the upper slopes of the valley and slid rapidly downhill carrying with it boulders and other debris. Sugar cane conceals the landslides.

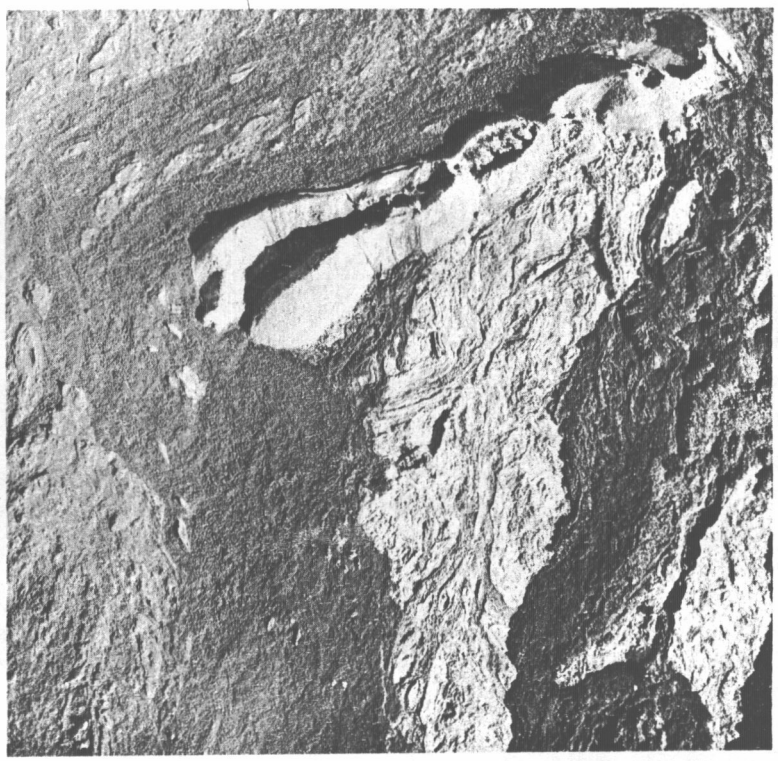

Fig. 8-5. Oblique aerial view of Lava Plastered Cones and the 1823 flows (dark-toned units) that erupted from the Great Crack. The name for the cones is derived from the "splash marks" and "high lava marks" left on the cones by the extremely fluid flow.

10. Punaluu junction. A side road leads to Punaluu where springs discharge about 95 million liters a day into the ocean from the basal zone of saturation. Similar springs also lie 2.4 km farther southwest at Kawaa. Inland are the prominent hills of Kaumaikeohu, Puu Enuhe, Kaiholena, and Puu One, high ridges of an ancient surface formed in Ninole lavas by stream erosion. The valleys between the ridges, originally much deeper, have been partly filled with later lavas. Faults crossing Kaiholena Ridge, northwest of Hilea, have formed a small graben.

11. Honuapo. Kahuku lavas and Pahala ash buried by a thin cover of Ka'u lavas are exposed along the road west of Honuapo.

12. Waiohinu. Between Naalehu and Waiohinu the road crosses a broad kipuka covered with Pahala ash. West of Waiohinu the road climbs the face of a steep cliff from which an excellent view is obtained of the Waiohinu rotational fault which forms a black ledge running seaward. The earthquake of April 2, 1868, destroyed every building in Waiohinu and horizontal movement caused the old road crossing the Waiohinu fault to be offset about 2.5 m.

13. Kahuku Pali. Near the lower end of the branch road to South Point, the top of Kahuku Pali is reached by a short walk westward. The pali is a fault scarp 152 m high at the base of which lies a branch of the lava flow of 1868. The fault can be traced about 16 km on land and an additional 28 km out to sea. The cliff is the type locality for the Kahuku lavas. They are capped by Pahala ash. A trail leads 4.9 km northeast of South Point to Papakolea where wave erosion of a littoral cinder cone of the Kahuku volcanic series has resulted in a green beach composed largely of olivine sand.

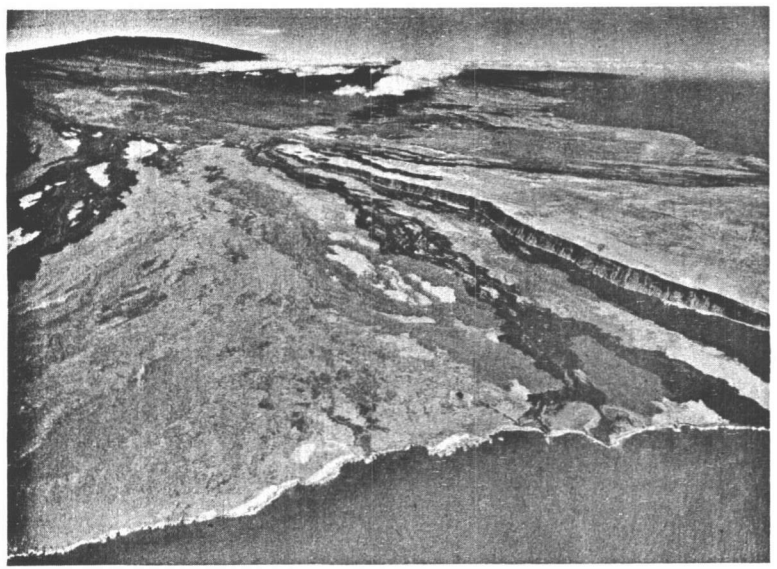

Fig. 8-6. Oblique aerial view of the Kahuku Pali toward the summit of Mauna Kea. Dark flows at the base are the 1868 flows from Mauna Kea. (*U.S. Navy photograph, 1954.*)

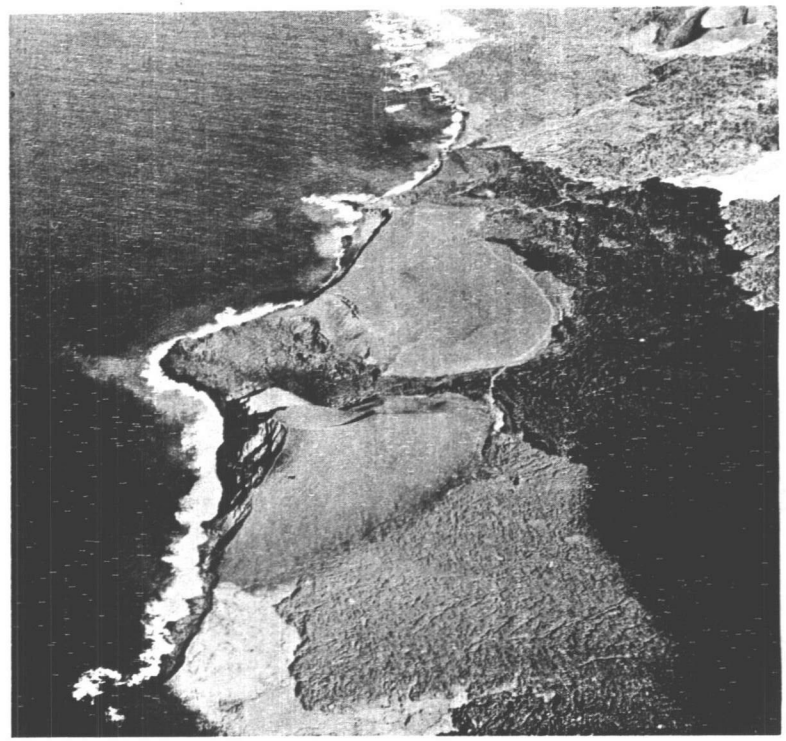

Fig. 8-7. Oblique aerial view of Puu Hou, a littoral cone near Kahuku Pali, formed when 1868 flows entered the sea. (*U.S. Geological Survey-Hawaiian Volcano Observatory photograph by John Lockwood, June 1974.*)

14. Historic lava flows. Between 0.8 and 4 km west of the South Point road the highway crosses the Mauna Loa lava flow of 1868 which issued from fissures 0.8 to 5.7 km above the highway and flowed into the ocean. The aa lava flow of 1887 is crossed 7.3 km west of the South Point road. It originated on the southwest rift zone 14.6 km above the highway, and flowed into the ocean. West of the lava of 1887, the highway crosses the eastern branch of the lava flow of 1907. The western branch lies 5.7 km farther west. Both branches issued from a fissure in the southwest rift of Mauna Loa 13 km above the highway.

15. Lava flow of 1926. 1.6 km south of the junction with the branch road to Hoopuloa and Milolii, the highway crosses the Mauna Loa aa flow of 1926 which destroyed the small fishing village of Hoopuloa. Some of the Hawaiians have rebuilt their homes on the top of jagged bare lava. On its surface are prominently displayed large accretionary lava balls formed by viscous lava wrapping around solid fragments.

16. Lava flow of 1919. About 2.4 km north of the junction, the highway crosses the Mauna Loa flow of 1919, which issued from a fissure in the southwest rift zone at an altitude of 2348 m (7700 ft). Explosions occurred where the lava flowed into the sea, sending great rolling clouds of steam and ash into the air, building a littoral cone, and killing numerous fish.

Between this point and Hookena (about 15 km to the north), the road crosses three flows from the 1950 eruptions on the southwest rift zone of Mauna Loa.

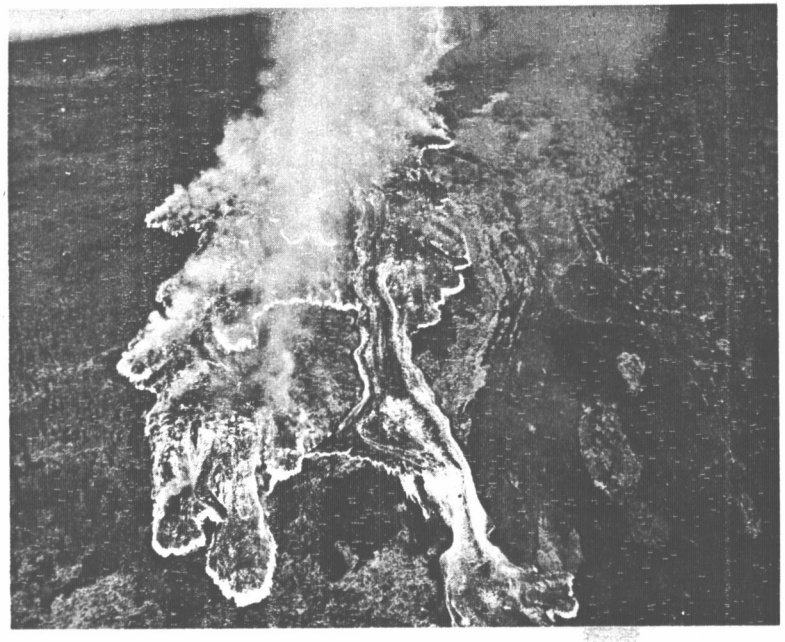

Fig. 8-8. Oblique aerial view of one of the 1950 flow from Mauna Loa. (*Photograph by the Hawaii Air National Guard, contributed by the Hawaiian Volcano Observatory.*)

17. Honaunau. A short side trip leads to the ancient Hawaiian City of Refuge at Honaunau (national historical park), with its partly restored ruins of stone temples. The ground was considered sacred, and political or military fugitives gaining its sanctuary were safe from their pursuers. It is situated on a small peninsula built into the sea by a pahoehoe lava flow. Brackish springs issue in the cove nearby.

18. Napoopoo. An excellent view may be obtained of Kealakekua Bay. The cliff on the northern side of the bay is believed to be a fault scarp, somewhat modified by wave erosion, exposing Kahuku lavas. The scarp extends inland in a southeasterly direction, but is heavily veneered with later lavas of the Ka'u volcanic series. A monument marks the place on the northwestern shore of the bay where Captain James Cook was killed in a dispute with the natives. The small patch of ground on which the monument is situated is the property of Great Britain.

19. Kainaliu. About 1.6 km to the north the lavas change from those of Mauna Loa to those of Hualalai, but the lavas are so similar, the change cannot be detected.

20. Kailua. On clear days an excellent view may be had of Hualalai Volcano and the line of cinder and spatter cones which marks its northwest rift zone. Numerous large lava tubes have been found in this area.

21. Lava flow of 1801. Half a mile below the road can be seen the source cone of the Huehue lava flow of 1801, the last flow from Hualalai Volcano. The lava extends to the sea, spreading out to a width of more than 4.8 km.

22. Kaupulehu lava flow. About 4.8 km northeast of the Huehue Ranch the highway crosses the Kaupulehu lava flow of 1800-1801. The channels of the flow are prominent, and in many places exhibit walls coated with a thin shiny veneer of late lava and lava stalactites. The lava contains many gabbro and dunite inclusions brought up from depth and scarce large clear crystals of feldspar.

Fig. 8-9. Mafic and ultramafic nodules coated with a thin veneer of basaltic lava in the 1800-1801 Kaupulehu Flow from Hualalai. The lava was extremely fluid and the nodules collected as "lag concentrates" along sections of the various lava channels of the flow. At least eight distinct beds of nodules occur in the vicinity of hornitos near the Hue Hue telephone repeater station at the 930 m level (3050 ft), about 1.8 km upslope from the highway (Dale Jackson, personal communication, 1974). Pen indicates scale. (*Photograph by Ronald Greeley, University of Santa Clara, 1973.*)

23. Branch road to Puu Waawaa Ranch. Puu Waawaa, 3.2 km inland, is a cone of trachyte pumice (at present, is being quarried), much gullied by intermittent stream erosion. North of the Puu Waawaa Ranch road, the highway climbs a steep escarpment which marks the edge of a thick trachyte flow from Puu Waawaa. The edge of the trachyte is partly veneered by later thin cascades of basalt. The trachyte, a light gray rock, is exposed in road cuts.

24. Lava flow of 1859. The highway crosses the Mauna Loa pahoehoe flow of 1859 which extends as a black ribbon from an altitude of 3355 m (11,000 ft) to the sea, a distance of 52 km. The flow lasted 7 months, extruding about 310×10^6 cubic meters of lava, the most voluminous flow in historic time. The pahoehoe accumulated undersea in masses of ellipsoidal bodies known as pillow lava.

25. Contact of Mauna Loa and Mauna Kea lavas. After leaving the lava flow of 1859 the highway continues for 7.3 km over lavas of Mauna Loa. Then thick bumpy andesite aa flows of the Laupahoehoe volcanic series are seen indicating that the Mauna Kea lavas have been reached. These extend northeastward for 4 km to the smoother ash-covered lavas of the Hamakua series. Numerous cinder cones are visible from the road.

26. Waimea (Kamuela Post Office). A fine view of Mauna Kea may be had on a clear day from Waimea. For 17.8 km south of Waimea the highway crosses lavas of the Hamakua volcanic series of Mauna Kea, covered with Pahala ash. Just southwest of Waimea the ash has been largely swept away by the wind. The ash was derived chiefly from eruptions of Mauna Kea, with small contributions from Kohala vents. Waimea lies on a saddle formed by lavas from Mauna Kea banking against Kohala Mountain. The broad flat saddle is called Waimea Plain. Puu Pa, a cinder cone 4.9 km southwest of Waimea, contains many loose, well formed crystals of augite and olivine. Some of the augites are as much as 1.5 cm long.

27. Waimea Canyon. Three and two-tenths kilometers east of Waimea a side trip on foot or horseback of about 3.2 km over the Upper Hamakua ditch trail takes one to the brink of spectacular Waimea Canyon, 670 m deep, a tributary of Waipio Valley. Numerous springs issue from a dike swarm in its floor. A view can be had of the northwest-trending Kawainui branch of Waipio Valley. The ditch trail continues around the head of Koiawe to the head of Kawainui Canyon.

Three and two-tenths kilometers east of the Hamakua trail the highway crosses thick andesite flows of the Laupahoehoe volcanic series of Mauna Kea. They are well exposed in road cuts and quarries.

28. Honokaa. Between Honokaa and Hilo the highway crosses principally Hamakua lavas with a capping of Pahala ash, and occasionally a narrow tongue of andesite of the Laupahoehoe volcanic series.

29. Kukuihaele. From Honokaa a paved road leads northwestward to the rim of Waipio Valley, where an excellent view of the valley and the high sea cliffs along the northeastern coast of Kohala Mountain can be had. The valley was cut by stream erosion at a time when sea level was probably more than 300 m lower than now. A later rise of sea level caused depsoition of stream alluvium, forming the present flat valley floor. The great sea cliff appears to be the result of wave erosion. An excellent section of the Pololu lavas, capped by a single flow of andesite of the Hawi volcanic series, is exposed along the trail down the southeastern side of Waipio Valley. Lava from Mauna Kea spilled into the valley at Hiilawe Falls.

30. Paauilo. A quarry 1.2 km northwest of Paauilo shows clearly the internal structure of an aa lava flow, with its massive center and clinker phases at top and bottom. The flow rests on a thin bed of red ashy soil. A large Maui-type well at Paauilo yields water from the basal zone of saturation for washing sugar cane before it enters the mill.

31. Ookala. A Maui-type well yields water from the basal zone of saturation. About 1.6 km southeast of Ookala is a small viscous dome of andesite, the lowest vent in the Laupahoehoe lavas. From it a thick flow of andesite advanced northeastward about 800 m.

32. Laupahoehoe. An andesite lava flow spilled into the head of Laupahoehoe Gulch and partly filled it. Where it entered the sea the flow built a small lava fan which forms the present peninsula from which the Laupahoehoe volcanic series is named. Springs issuing in road cuts just south of Laupahoehoe Gulch are perched by beds of ashy soil. The south wall of Laupahoehoe Gulch is the type locality of the Hamakua volcanic series.

33. Maulua Gulch. The valley was eroded by a stream during a time when sea level was several hundred feet lower than now. Later, a rise of sea level caused alluviation of the valley floor.

34. Hakalau. The lavas of the upper member of the Hamakua volcanic series are well exposed in road cuts along the south side of Hakalau Gulch. They include olivine basalts, picrite-basalts, and andesites.

35. Honomu. An excellent view of Mauna Kea may be had from this point on a clear day. A branch road leads to Akaka Falls, where Kolekole Stream drops 126 m into a stream-eroded amphitheater cut into lavas of the Hamakua volcanic series.

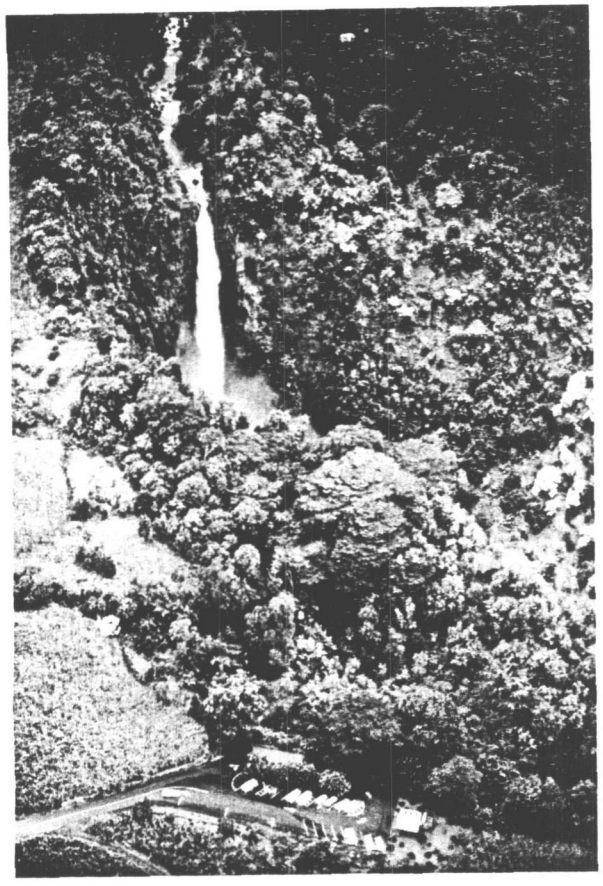

Fig. 8-10. Oblique aerial view of Akaka Falls. (*NASA-Ames Research Center photograph by Ronald Greeley, 1970.*)

36. Onomea Bay. The promontory forming the northern side of the bay is an old cinder cone, nearly buried by later lavas. Onomea Arch is the result of wave erosion of the cinder cone when the sea stood about 7.6 m higher than at present. Kawainui Stream formerly emptied into Onomea Bay. An andesite flow of the Laupahoehoe volcanic series descended the gulch of Kawainui Stream, diverted the stream to its present course, and built a small lava fan in Onomea Bay. Benches and notches cut when the sea stood 1.5 m above its present level are preserved on the andesite flow and along the edge of the cinder cone.

ROAD FROM OLAA TO KALAPANA VIA KAPOHO

(See also: Guide to East Puna, G. A. Macdonald.)

37. Lava flow of 1840. The road crosses the laval flow of 1840 which contains many crystals of olivine. This flow formed a littoral cone where it entered the sea. The next fresh flow to the southeast was erupted about 1790. At 4 km east of the 1840 flow, lava tree-molds occur in prehistoric pahoehoe 15.2 m north of the road. Some are 3 m high.

38. Kapoho. Kapoho Cone is a broad tuff cone made by explosions as magma rose through rocks saturated with sea water. Green Lake, which occupies its crater, is perched a few meters above sea level by silt and soil on the floor and walls of the crater. It is supplied by runoff from the surrounding slopes. Puu Kukae, a cinder cone, lies just east of Kapoho, its internal structure exposed in a quarry. Blue Grotto, a pool of water at the northern base of Puu Kukae, lies in a crevice along a fault. Formerly, the water was warm. The floor of a shallow fault trench just north of Puu Kukae was depressed 2.4 m at the seaward end during the earthquakes of 1924.

39. Kaakepa Cone. A littoral cone on the seaward side of the road, formed by the explosion of aa lava on entering the sea. Makaaiea Cone, 5.5 km to the southwest, has a similar origin.

40. Kalapana. The village is situated in a shallow fault trench, the floor of which subsided several meters in 1868. The low ridge south of the road just southeast of Kalapana is a small horst block elevated between two faults. The low cliff facing the road is a fault scarp. The Cave of Refuge is a lava tube. The entrance was walled up and made narrower, with a right-angle bend, to protect ancient Hawaiians who took refuge there from spears and sling stones. The black sand of the beach at Kalapana is composed largely of volcanic glass derived by wave erosion from a former littoral cone. The lava flow of 1750 (?) is the fresh black aa crossed by the road just northeast of Kalapana.

ROAD FROM HILO TO WAIMEA VIA HUMUULA SADDLE WITH A SIDE TRIP TO PIIHONUA

41. Halai Hill and two other small hills south of the road are ancient cinder cones on the northeast rift of Mauna Loa. These hills shielded the area now occupied by downtown Hilo from late prehistoric lava flows, thus accounting for the thick cover of ash in that area.

42. Rainbow Falls. The falls are caused by the Wailuku River cutting a large plunge pool at an unconformity. Exposed in the face of the falls is the cross section of an ancient valley filled with lava from Mauna Loa. Small springs issue at the base of this lava on the south side of the falls. North of the river are lavas of Mauna Kea covered with Pahala ash.

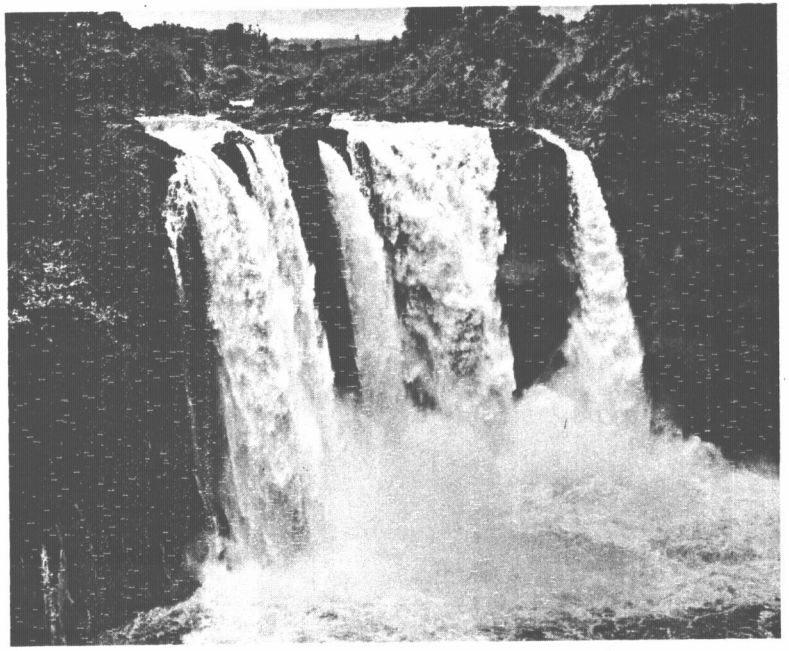

Fig. 8-11. Rainbow Falls on the Wailuku River, Hilo. (*Photograph by Ronald Greeley, University of Santa Clara, 1973.*)

43. Boiling pots. The Wailuku River has cut a series of large pot holes, some of which are connected beneath the surface, in the ancient valley-filling lava flow exposed at Rainbow Falls. The ancient valley was not entirely filled at the Boiling Pots, the top of the lava flow forming terraces 6 to 10 m below the rim of the valley.

44. Kaumana Cave. (See separate guide by Greeley.) A lava tube in the flow of 1881, ranging from 0.5 to 4.5 m high and 2.5 to 18 m wide, can be followed for more than 800 m. This lava flow, over which the road passes near Kaumana, extends from a point above an altitude of 300 m (10,000 ft) on the northeast rift of Mauna Loa to a point south of Halai Hill, a distance of 50 km. It flowed for 9 months and came closer to Hilo than any other historic flow. In road cuts between Hilo and Kaumana Cave, late lavas from Mauna Loa rest on Pahala ash.

45. Lava flow of 1855. For 14.6 km, the road passes over the lava flow of 1855. This eruption lasted 13 months, longer than any other historic Hawaiian flow.

46. Lava flow of 1899. It is difficult to separate this flow from the aa phase of the adjacent flow of 1855. One distinguishing mark is the less abundant vegetation.

47. Lava flow of 1935. The road follows this lava for about 13 km. The flow is partly pahoehoe and partly aa. Along the road can be seen a good example of pahoehoe following an older aa channel. The lava flowed toward the Wailuku River, endangering Hilo's water supply.

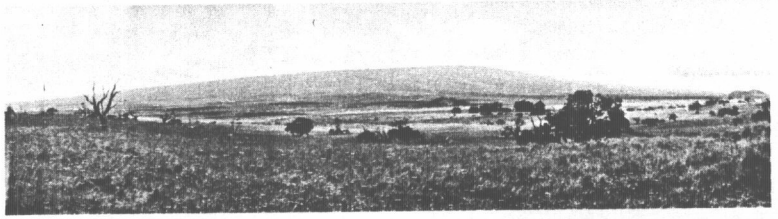

Fig. 8-12. Panoramic view southward of Mauna Loa ("long mountain") showing the typical gentle slopes resulting from voluminous eruptions of fluid lavas with relatively little production of pyroclastics. (*Photograph from slopes of Mauna Kea, altitude ~1850 m, by Dale Cruikshank, University of Hawaii.*)

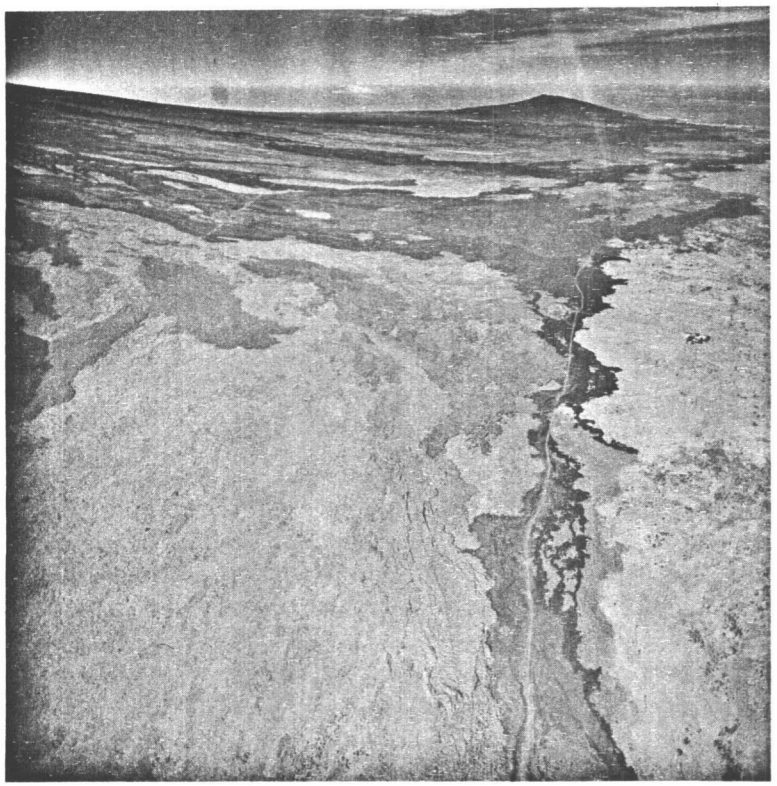

Fig. 8-13. Oblique aerial view westward across the Humuulu Saddle toward Hualalai Volcano. Road is State Route 20 (Saddle Road). Darkest lava is 1935 flow from Mauna Loa (summit out of view to the left). Small light patch in the middle of the flow, near the road, is Puu Huluhulu. (*U.S. Navy photograph, 1954.*)

48. Puu Huluhulu, at the junction of the Saddle Road and the road to the summit of Mauna Kea. A Mauna Kea cinder cone surrounded by Mauna Loa lava of 1935. It has been extensively quarried for road metal and the internal structure is well exposed.

49. Hale Pohaku. A side road leads to Hale Pohaku at an altitude of 9,350 ft on the southern slope of Mauna Kea where there are cabins for mountain climbers. The nights are cold and snow is common: hence, warm clothing should be carried. From Hale Pohaku a 10-km jeep trail leads to the summit of Mauna Kea. This section is scheduled to be paved in late 1974. The trail crosses lavas of the Laupahoehoe volcanic series and associated cinder cones. At 11,500 ft altitude is the terminal moraine of the small glacier which covered the summit of Mauna Kea in Pleistocene time, and above that altitude are ground moraine, roche moutonnées, and a few polished and striated rock surfaces, all indicative of the former glacier. Inclusions of gabbro and periodotite are found in the summit cones and in those west of Hale Pohaku.

50. Lava flow of 1843. This thick aa flow originated from a fissure at an altitude of 10,000 ft on the northern slope of Mauna Loa. On leaving the lava, the road turns sharply northward along a row of cinder and spatter cones which apparently belong to Mauna Loa.

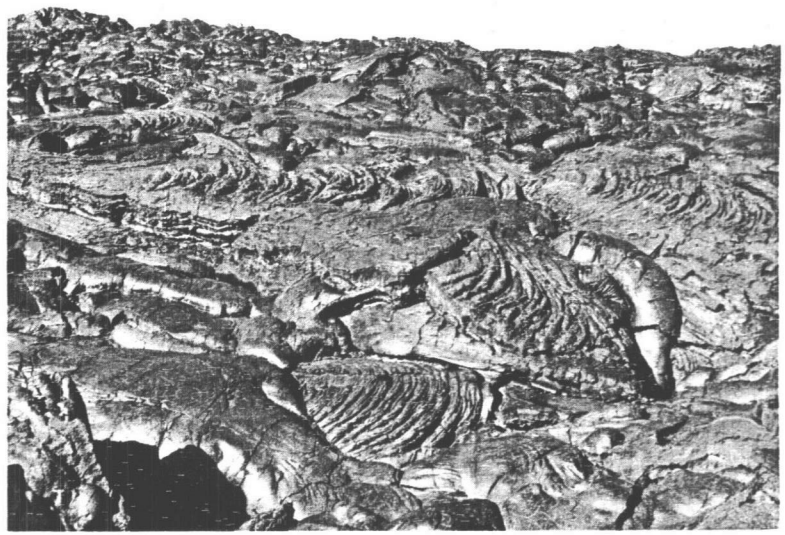

Fig. 8-14. Pahoehoe lava of the 1935 flow, Humuula Saddle area. View northward with Mauna Kea in the background. (*Photograph by Dale Cruikshank, University of Hawaii.*)

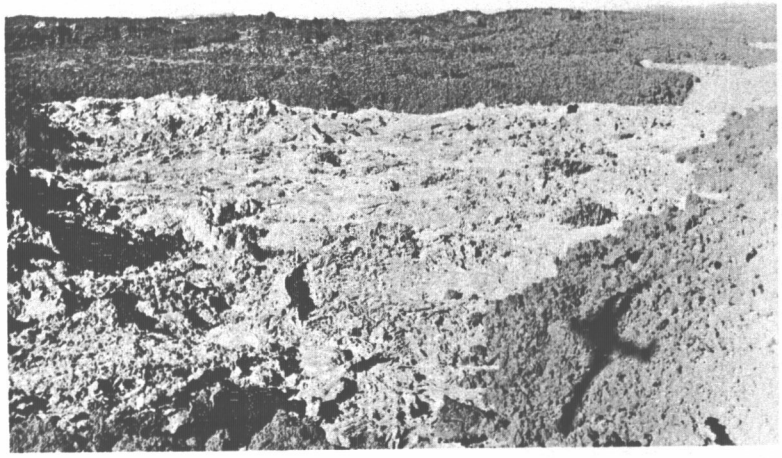

Fig. 8-15. AA lava (dark-toned flows) on the slopes of Mauna Loa, Humuula Saddle area. (*Photograph by Dale Cruikshank, University of Hawaii.*)

51. Pohakuloa Camp. The terminal moraine of the glacier is clearly visible on the slopes of Mauna Kea far above the camp as a light colored firnge of rock. Near the camp and for 8 km to the west the road passes over gravel deposits formed partly by flood stream deposition under present conditions and partly as outwash deposits from the voluminous melt waters which accompanied the recession of the glacier.

52. Sand dunes. The road, 3 to 5 km south of Waikii, crosses dunes of black sand, glassy volcanic ash erupted from cones on the slopes of Mauna Kea.

53. Puu Kawaiwai. A late andesite cinder cone of Kohala Mountain, well exposed by quarrying. In the vicinity of Puu Kawaiwai the road crosses basalts of the Pololu volcanic series, with a thin ash cover. Three kilometers northwest of Puu Kawaiwai the lavas change to andesites of the Hawi volcanic series, and the road continues over them for about 14.5 km.

54. Kahua Ranch. The large cinder cones along the road were made by fountains of viscous lava of the Hawi volcanic series. The cones lie in the north rift zone of Kohala Mountain. The beautiful Kehena ditch horse trail starts near this point and leads around the head of Honokane Nui Canyon, 800 m deep.

55. Hawi. The sugar cane around Hawi grows chiefly on deeply weathered Pololu lavas. The water to irrigate the fields is diverted from the great canyons and rivers to the southeast by a remarkable ditch and tunnel system 29 km.

56. Mahukona. In the short stretch of 11 km from Hawi to Mahukona one passes from the windward and rainy side of the island to the leeward dry side. The fertile red-brown soil, 3 to 6 m deep and covered with crops, thins to 0.6 m or less of red soil sparsely covered with desert vegetation. The rocks along the road are the same age; the change in soil depth is due solely to decrease in rock decomposition with increase in aridity.

57. Pololu Valley. A fine view of the valley and the high sea cliff of northeastern Kohala Mountain can be obtained. Pololu Valley has been partly filled by a late flow of andesite. A side trip on foot or horseback along the Kohala ditch trail leads through rainforest jungle to the spectacular Honokane Nui Canyon, in the head of which is a tunnel developing large quantities of ground water from a dike swarm 600 m above sea level.

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9. FIELD GUIDE TO SUMMIT AREA AND UPPER EAST RIFT ZONE, KILAUEA VOLCANO, HAWAII

Hawaiian Volcano Observatory Staff
United States Geological Survey
Hawaii Volcanoes National Park, Hawaii 96718

9. FIELD GUIDE TO SUMMIT AREA AND UPPER EAST RIFT ZONE, KILAUEA VOLCANO, HAWAII

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Kilauea Volcano occupies the southeastern part of the island of Hawaii. It is built primarily of countless thousands of lava flows of tholeiitic basalt and rises from the sea floor, about 4,600 m below sea level, to a height of 1,247 m above sea level. Its summit area is occupied by a caldera about 3 by 4 km in diameter with a maximum distance from rim to floor of about 120 m. The volcano has two rift zones that extend outward from the summit down the flanks – an east rift zone and a southwest rift zone (Fig. 9-1). All of Kilauea's known eruptions have taken place either from the summit area or from one of the rift zones.

Kilauea has had more than 50 eruptions in historic time; those prior to 1969 are summarized by Macdonald and Abbott (1970, p. 74-75). Historically, Halemaumau has been Kilauea's most active vent, as it was active almost continuously from 1823 to 1924 and erupted vast quantities of lava onto the caldera floor. Explosive activity, rare in Hawaii, greatly enlarged Halemaumau in 1924, and since then its eruptions have been episodic. Kilauea did not erupt from 1934 to 1952. From 1952 to the present, Kilauea has erupted 25 times, including eruption at the summit and along both rift zones. Activity has varied widely both in duration and character; eruptions have lasted from a few hours to 2-1/2 years and have ranged from gentle bubbling in vents, to quiet outwelling of lava, to roaring fountains as high as 580 m.

Studies by the Hawaiian Volcano Observatory, U.S. Geological Survey, have greatly enhanced the understanding of Hawaii's volcanoes. Geological, geophysical, and geochemical studies are carried out by a staff that currently numbers 16. Eruptive events are described, eruptive products are sampled, vents and flows are mapped, and a photographic record is kept. Seismic events are recorded by 35 seismic stations located throughout the island. Ground deformation is monitored by tilt measurements, leveling surveys, and periodic remeasurement of distances in a trilateration network by Geodimeter. Other geophysical methods used to monitor include resistivity, electromagnetic, magnetic, and gravity studies; of particular current interest are self-potential studies. Petrologic and chemical studies are aimed at developing improved hypotheses of magmatic history and evolution. The improving understanding of volcanic processes has also led to better forecasting techniques and enhanced knowledge concerning the hazards to human life and activity posed by Hawaiian volcanoes.

The field trip is divided into two sections: (1) Crater Rim Road; (2) Chain of Craters Road. Most bibliographic references are omitted from the text, but a selected list of references to recent Hawaiian volcanic activity and to special studies is included.

SECTION 1: CRATER RIM ROAD

Stop 1 – Hawaiian Volcano Observatory; Kilauea Caldera

The viewing platform outside the U.S.G.S. Hawaiian Volcano Observatory (HVO) offers an excellent view of Kilauea Volcano's summit area and provides an appropriate vantage point for briefly reviewing the relations of Kilauea Caldera, Halemaumau Crater, the southwest and east rift zones of the volcano, and the geologic changes in the summit area during historic time (Fig. 9-2). From the HVO platform, a view may be obtained of the newest large landform in the United States – the volcanic shield of Mauna Ulu – can be seen southeast across the summit caldera.

"Mauna Ulu" in Hawaiian means "Growing Mountain," and the name, coined in 1970, has proven very apt. Mauna Ulu has grown in spurts, and its latest spurt in 1974 added about 45 m to its height, which is presently about 121 m. Recent changes can be seen by comparing the profiles of Mauna Ulu as viewed from HVO in March and in June 1974 (Fig. 9-3).

After the outdoor orientation, a brief tour of the observatory will be provided, and current research at HVO will be reviewed. Then we will travel counterclockwise around the south side of Kilauea Caldera.

Stop 2 – Southwest rift zone of Kilauea Volcano

An eruptive fissure cut the Crater Rim Road here on 24 September 1971. This was the first eruption on Kilauea's southwest rift in more than 50 years. The eruption began at 19:20 on

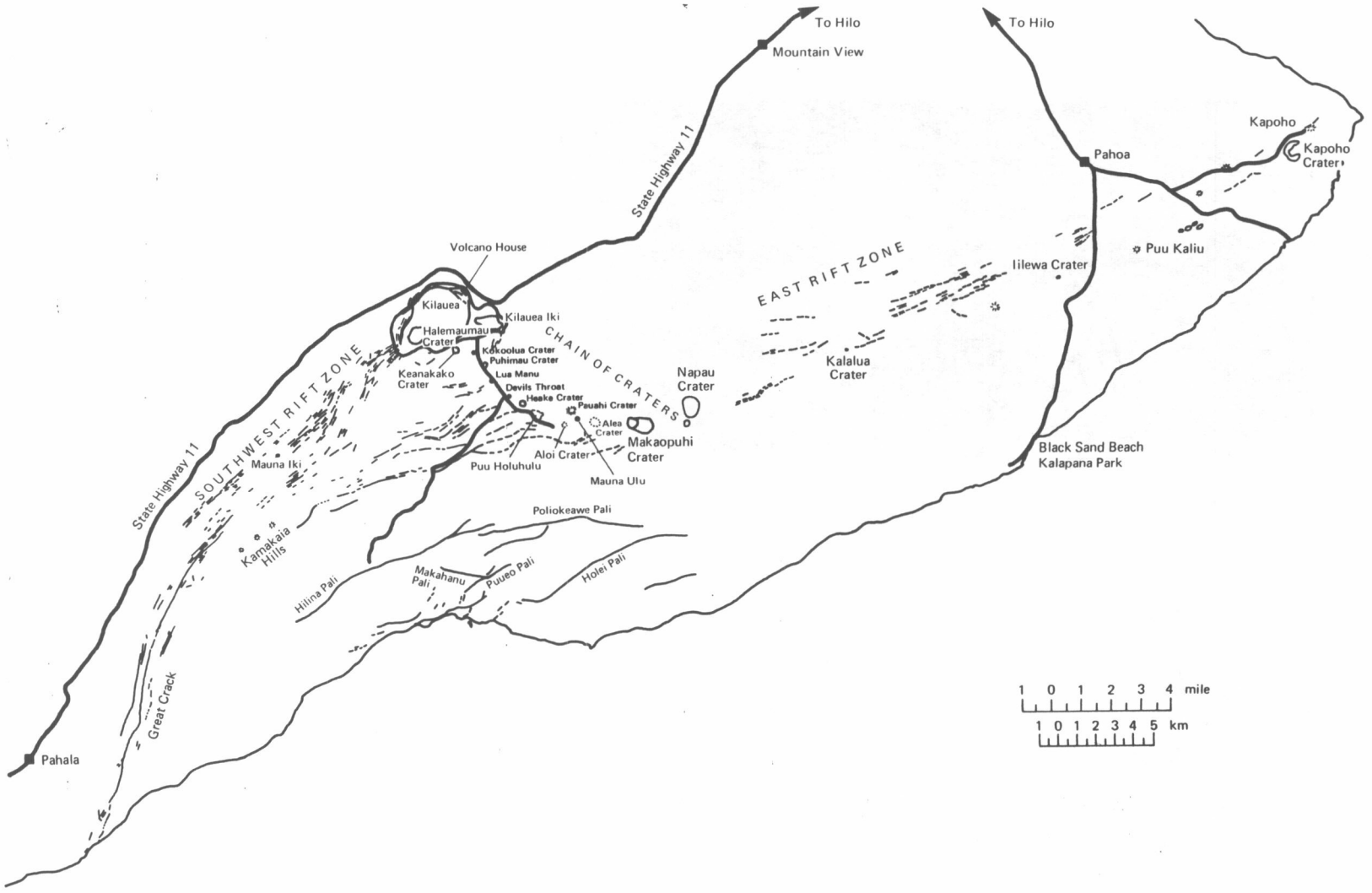


Fig. 9-1. Sketch map of Kilauea Volcano, Hawaii. (*Base maps U.S. Geol. Survey 15' quadrangles Pahala, Kilauea, Puna, Kalapana, Hilo and Makuu.*)

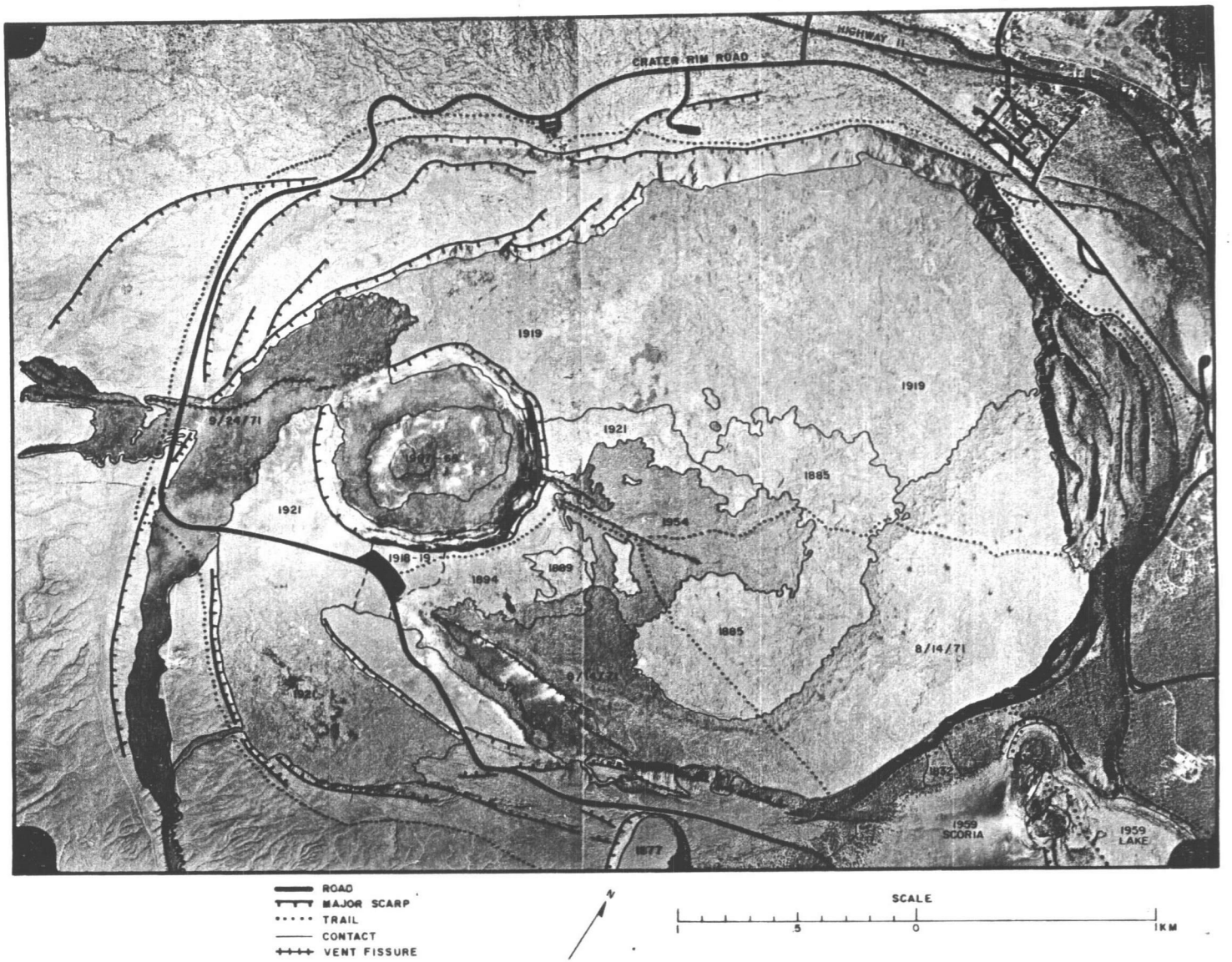


Fig. 9-2. Photogeologic map of Kilauea caldera showing principal features and flows as of June 1974. (*Aerial photographs by R. M. Towill Corporation, Honolulu, 1972.*)
Editor's note: An eruption in July, 1974, covered much of the August 1974 flow.

24 September, formed a line of lava fountains (the "curtain of fire") in Kilauea Caldera west of Halemaumau, quickly flooded the southwestern part of the caldera floor, cascaded into Halemaumau, and formed a flow that extended out of the caldera to the south. About half an hour later a lava fountain vented in Halemaumau, and by about 20:00 new fountains extended into both the southwest rift zone and the caldera on the east side of Halemaumau. Lava from the caldera floor poured into Halemaumau along the east wall of the crater. Thus, less than an hour after start of the eruption, lava was fountaining along a discontinuous line of fissures extending about 2 km, from the central part of the caldera, through Halemaumau, and into the southwest rift zone. The outbreak along the southwest rift zone was immediately preceded and accompanied by extensive ground cracking, and the line of fountains gradually advanced southwestward for nearly a kilometer. As the head of the line advanced, the tail followed, so a discrete line about 150 m long migrated downrift. The fountains at the tail of the line became progressively lower and more gassy, and eventually became roaring gas vents that reamed out the bedded pyroclastic deposits of the upper vent walls.

Activity in the caldera started to wane about an hour after it began but continued along the southwest rift zone until about 22:20. Most of the activity in Halemaumau ended near midnight, but some vents on the east wall continued for another day. Early on 25 September, the main activity at Halemaumau decreased and the floor began to subside. By 07:30 it had collapsed at least 20 m. After the eruption the total subsidence of Halemaumau's floor was measured as 45 m. Meanwhile, at about 10:00 on 25 September, eruptive activity resumed on the southwest rift zone about 3 km downrift from the Crater Rim Road. Fountains continued to migrate downrift through the next day and eventually reached 11 km from the caldera. For the next four days, activity was sporadic at various localities along the 8-km span of the eruptive zone, and the eruption ended on 29 September. A zone (averaging about half a kilometer wide) of new ground cracks extended the length of the eruptive zone. Later measurements showed that a zone of uplift and extension coincided with the band of new ground cracks and eruptive fissures.

Stop 3 – Low point of the caldera rim

Lava from the September 1971 eruption crossed the caldera rim near here and flowed nearly 3 km to the south. From this point, an excellent view may be obtained of the lava-subsidence terrace ("bathtub ring") formed by the 1971 lava at its high stand along the west wall of the caldera. Holcomb (1973) suggested that such lava-subsidence terraces can be used as natural tiltmeters on planetary surfaces to assess posteruptive deformation.

Stop 4 – Halemaumau

In this general area explosion debris from the 1924 phreatic explosions in Halemaumau (Fig. 9-4) covers pahoehoe formed in 1894 and 1918-19. If fume and weather conditions permit, a view of the crater floor and stratigraphy of the walls may be seen from the overlook point on the east rim of Halemaumau.

When the first recorded visit to Kilauea was made in 1823 by William Ellis, the caldera floor was about 150 m lower than it is today. Throughout much of the nineteenth century Halemaumau was a complex of vents and a lava lake, from which lava frequently poured out onto the caldera floor. The filling of the caldera was interrupted several times by major draining events, during which Halemaumau collapsed to leave a deep pit crater. The crater of Halemaumau contains the main vent and is at the summit of a gently sloping shield in Kilauea Caldera. This shield can be clearly identified in the view from north to east across the caldera from the rim of Halemaumau.

Continuous lava lake activity at Halemaumau ended with the phreatic eruption of 1924. The lava column in Halemaumau dropped drastically from February through May of 1924 and was accompanied by intrusive and perhaps extrusive activity on the east rift zone from near the summit to below sea level. On 11 May 1924 a series of increasingly violent steam-driven explosions from the crater began and continued intermittently for two weeks. Clouds of dust from the explosions rose more than 6 km high, and lithic ash and blocks ejected by the explosions covered wide areas near the crater. These explosions produced no new lava and were evidently caused by groundwater entering the volcanic conduit as the east rift activity drained magma from the summit. The entire summit area of Kilauea subsided, locally as much as 3-1/2 m. The diameter of Halemaumau Crater nearly tripled, and the pit at the end of the 1924 eruption was choked off by talus and avalanche debris at a depth of 400 m. Continuous lava lake activity has not resumed at Halemaumau since the 1924 phreatic eruption, but lava has erupted in the crater on 14 occasions since then and has raised the level of its floor. The eruption of 1967-68 lasted for more than 8 months and included a lava lake and many episodes of fountaining, that added about 120 m of new lava to the crater floor.

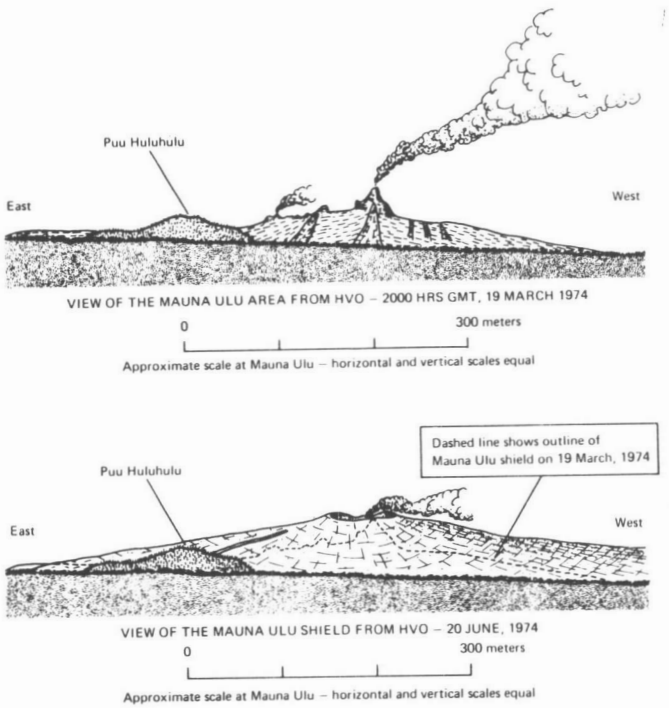


Fig. 9-3. Comparative profiles of Mauna Ulu, seen from Hawaiian Volcano Observatory viewing platform. (*From sketch by John P. Lockwood, U.S. Geol. Survey-Hawaiian Volcano Observatory.*)

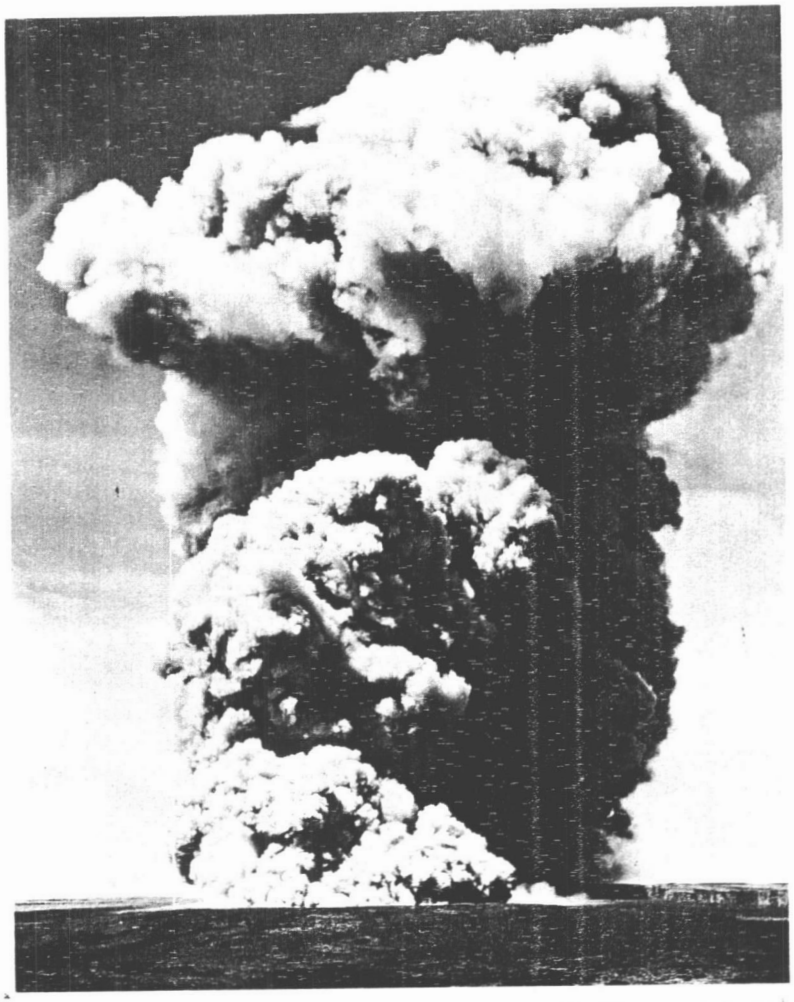


Fig. 9-4. Phreatic eruption at Halemaumau, 24 May 1924. (*Photograph by Tai Sing Loo.*)

The walls of Halemaumau conspicuously reveal the collapse of 25 September 1971. The crater floor lies about 80 m below the east rim, and an annular bench about 35 m below the rim shows the level of the floor at the end of the 1967-68 eruption. The cones near the center of the floor formed late in the 1968 eruption and were virtually undisturbed during the 1971 subsidence.

Stop 5 – Lava-filled gully

Lava from the eruption of 14 August 1971 poured through this gully and onto the caldera floor (Fig. 9-5). This eruption began at 08:55 with the opening of fissures on the southern floor of Kilauea Caldera (Fig. 9-2). A "curtain of fire" erupted from two en echelon fissures about 1.2 km long on the caldera floor and were soon joined by ground cracking and lava fountaining along a set of fissures about 700 m long on the caldera rim north of Keanakakoi. Lava fountains reached a maximum height of 70 m. Eruption from the caldera-rim fissures, near Stop 6, ceased after about an hour and a half, but fountaining continued in the caldera for about 10 hours. Lava from the fissures north of Keanakakoi formed spectacular cascades over the caldera rim and down gullies to join the lava on the floor. Flows covered the eastern and southern parts of the caldera floor; about 10 million m^3 of lava were erupted that covered about a fifth of the caldera floor. After the eruption of lava ceased, burning gases continued to escape from the vents for about 8 hours, and the vents in the caldera even now produce abundant steam and fume. Heavy incrustations of sulfur are accumulating around several of the western vents.

Editor's note: An eruption in July 1974 produced lava flows in this vicinity, many of which cover the 14 August 1971 flows on the caldera floor.

Stop 6 – Keanakakoi

Keanakakoi pit crater, prehistoric in age, is floored by dense pahoehoe lava erupted in 1877. The crater floor, as well as the surrounding area, is mantled by several centimeters of tephra from the 1959 Kilauea Iki eruption. Large boulders have fallen to the floor of the crater, possibly during the April 1973 magnitude 6.2 earthquake, and have left tracks across the surface of the tephra-mantled crater floor. These tracks are perhaps similar to boulder tracks identified in mountainous areas of the lunar surface.

Stop 7 – South end of Devastation Trail

The effects of repeated ash and scoria falls during the 1959 Kilauea Iki eruption can be seen along the Devastation Trail. The Kilauea Iki eruption, which lasted from mid-November to mid-December, produced the highest fountains (580 m) recorded at Kilauea. These fountains generated large volumes of ash, scoria, and reticulite, most of which was carried southwestward by the tradewinds to form the cinder cone, Puu Puai, and the thick blanket of tephra over which the Devastation Trail winds (Fig. 9-6). The trees here were stripped of their foliage during the eruption but are now particularly healthy, apparently refreshed by added nutrients and the extreme natural pruning.

Stop 8 – Kilauea Iki overlook (north end of the Devastation Trail)

The 1959 eruption of Kilauea Iki lasted for 36 days and went through 17 separate phases of fountaining. The fountains lasted from 1-3/4 hours to a week, and most episodes ended with a partial drainback of lava into the eruptive vent. By the end of the eruption, Kilauea Iki contained an accumulation 100 m deep of about 38 million m^3 of new lava (Fig. 9-7). The principal vent for the 1959 eruption lies at the north base of Puu Puai.

The 1959 Kilauea Iki eruption was part of a complex episode of volcanic tumescence, summit eruption, flank eruption, and summit deflation that lasted from 1957 through the summer of 1960. The HVO geophysical network had been recently expanded, and the 1959-60 eruptive cycle provided new insight into the volcanic mechanism of Kilauea. Core drilling was carried out and has been repeated at various intervals in the crusted surface of the Kilauea Iki lava lake. Observations of changing thickness of the lava crust, temperature profiles, and samples of crystallizing melt have been obtained from these drill holes.

Stop 9 – Thurston Lava Tube

A short walk from the parking lot leads through a dense rain forest to a small pit crater from which the Thurston Lava Tube may be entered. A trail leads through a segment of the tube about 120 m long, but the tube extends another 455 m before pinching out. Collapsed roof segments downslope suggest that the tube system may be several kilometers long.

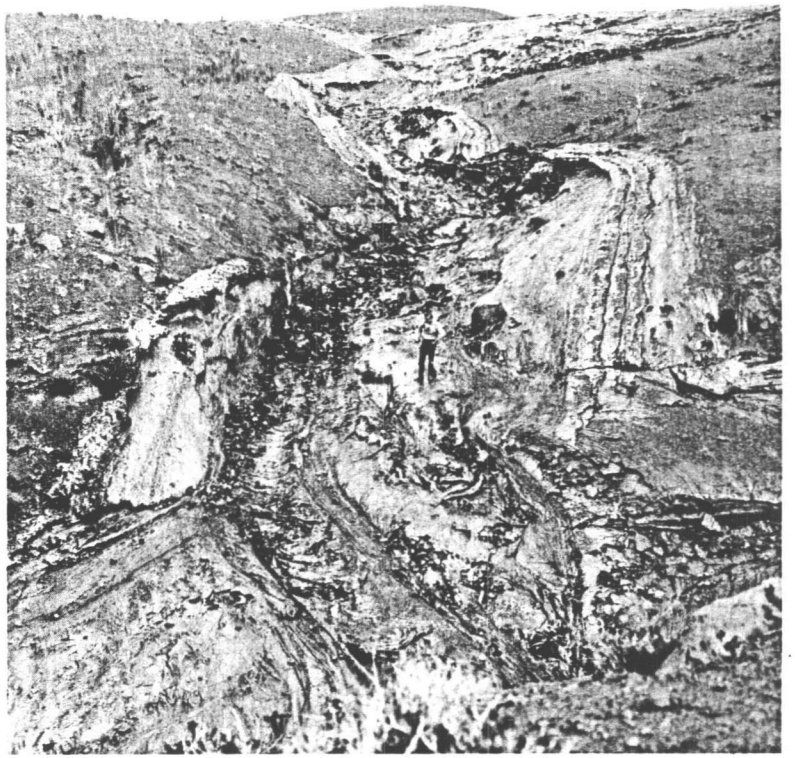


Fig. 9-5. View of "high lava" benches formed during the August 14, 1971 rift eruptions at Kilauea. Lava flowed from fissures along the caldera rim and down an existing stream channel (here) onto the floor of Kilauea. (*Photograph by Ronald Greeley, University of Santa Clara, 1973.*)

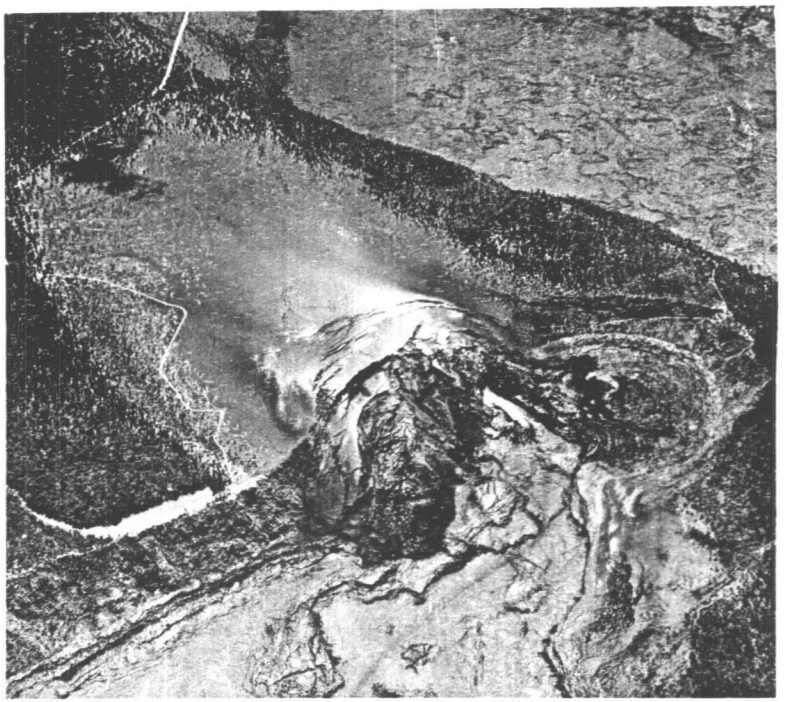


Fig. 9-6. Oblique aerial view of Puu Puai, the cinder cone of the 1959 eruptions at Kilauea Iki. Note the blanket of tephra that extends southwest from the cone. The white zig-zag line on the tephra is the boardwalk of the Devastation Trail. (*U.S. Air Force photograph, 1966.*)

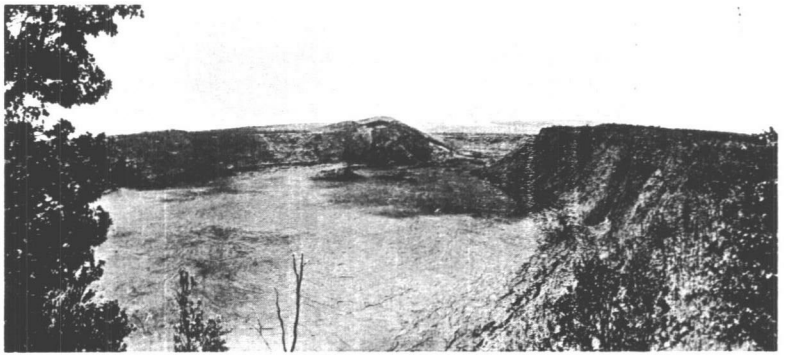


Fig. 9-7. Panoramic view westward across Kilauea Iki Crater, through a breach in the crater wall toward Kilauea Caldera. Note the slump scarp around the margin of the 1959 lava lake, showing subsidence of the lake surface. (*Photograph by Dale Cruikshank, University of Hawaii.*)

SECTION 2: CHAIN OF CRATERS ROAD

Kilauea's upper east rift zone is the site of recent and current (June 1974) eruptions.

The Chain of Craters Road passes Lua Manu and Puhimau Craters before reaching Kokoolau Crater and the area of Fig. 9-8. These are the only pit craters on the upper east rift zone that have not been the sites of eruptions in historic time.

All the pit craters on the upper east rift zone are nearly circular in plan view and apparently formed by collapse because there is no mantle of ejected debris around them. Collapse is thought to occur over open spaces that formed by withdrawal of magma or by dilation of the rift zone.

Several conspicuous horizontal offsets of the road center line can be seen near the intersection of Chain of Craters and Hilina Pali roads (Fig. 9-8). These have resulted from dilation of cracks that cross the road obliquely. The apparent movement on the faults is right lateral, but the actual ground motion was perpendicular to the trend of the individual faults rather than along the fault planes.

Hiiaka Crater (shown as "Heake" on Fig. 9-8) was the site of the first vent of the August 1968 eruption. This eruption lasted several days but produced only a small amount of lava. Fissures opened progressively downrift during the eruption, and the final vent was 24 km east of Hiiaka. Vents within and near Hiiaka Crater were also active during the eruption of 5 May 1973 when lava fountained as high as 50 m. New lava covered parts of the forest south of Hiiaka and formed a pool within the crater. Near the closing stages of activity, lava erupted briefly from a fissure in the eastern part of the Koae fault zone about 1 km west of Hiiaka. This was the first historic outbreak from this fault zone.

Stop 1 – Pauahi Crater (Fig. 9-8)

This composite, triple-pit crater was the site of the initial outbreak of the eruption of 5 May 1973 as well as the focal point of the eruption of 10-11 November 1973. The lava erupted here was apparently derived from the same magma reservoir that feeds the Mauna Ulu vent, 2.5 km to the east, as both eruptions at Pauahi were preceded by a sudden draining of Mauna Ulu's summit lake. Each eruption began at Pauahi Crater approximately 4 hours after strong harmonic tremor and precipitous deflation of Kilauea's summit region accompanied the sudden draining of Mauna Ulu's summit lake. On 5 May, the activity at Pauahi lasted about 2 hours, forming a lava pond in the western crater. After a brief lull, the activity moved uprift to Hiiaka. On 10 November, eruptive fissures opened first on the north wall of Pauahi's east pit at 21:47 with fountains as high as 70 m, then in the west pit and outside the crater. The fountains fed cascades down the crater walls forming lava ponds that were simultaneously drained through fissures in the crater floor. Activity was intense for several hours, then gradually declined, and virtually stopped by sunrise of 11 November. Weak but persistent activity continued in Pauahi's west pit for about a month. On 9 December all visible activity in Pauahi stopped, and from 9 to 12 December no harmonic tremor was recorded on any Kilauea seismographs. The high stand of lava in Pauahi's east lake is well recorded by a prominent lava-subsidence terrace visible on the walls of the east pit. The large talus cone in the west pit largely formed from a rock fall in March 1974.

Spectacular lava trees (Fig. 9-9) are well preserved both east and west of Pauahi Crater; these record the high stand of lava on the night of 10 November. Some lava trees were drenched with spatter from low fountains from an adjacent fissure after the surface had fallen to a lower level.

Stop 2 – Parking lot, Mauna Ulu trail

About 100 m east of the parking lot, the Chain of Craters Road is cut by a pahoehoe flow of the 10-11 November 1973 eruption; this is overlain by an aa flow of 25 January 1974. These are but two of many flows to cross the road since it was first cut by lava on 22 February 1969. At the present time (June 1974), a public hiking trail leads to the summit of Puu Huluhulu, a prehistoric lava and spatter cone about half a kilometer north of Mauna Ulu. Public access to the area varies according to eruptive conditions – *do not attempt to go into areas not authorized by the National Park Service.* If conditions permit at the time of the Planetology Conference, HVO personnel will lead the group to the summit of Mauna Ulu to view the vent configuration and any volcanic action that happens to be underway.

The walk to the summit of Mauna Ulu is about 2 km long; the first part is on the public trail, mostly over pahoehoe erupted in November 1973, and the last part is cross-country up Mauna Ulu's flank on lava as little as 3 weeks old at this writing. Intricate structural patterns may be noted on the surface of pahoehoe. These complicated

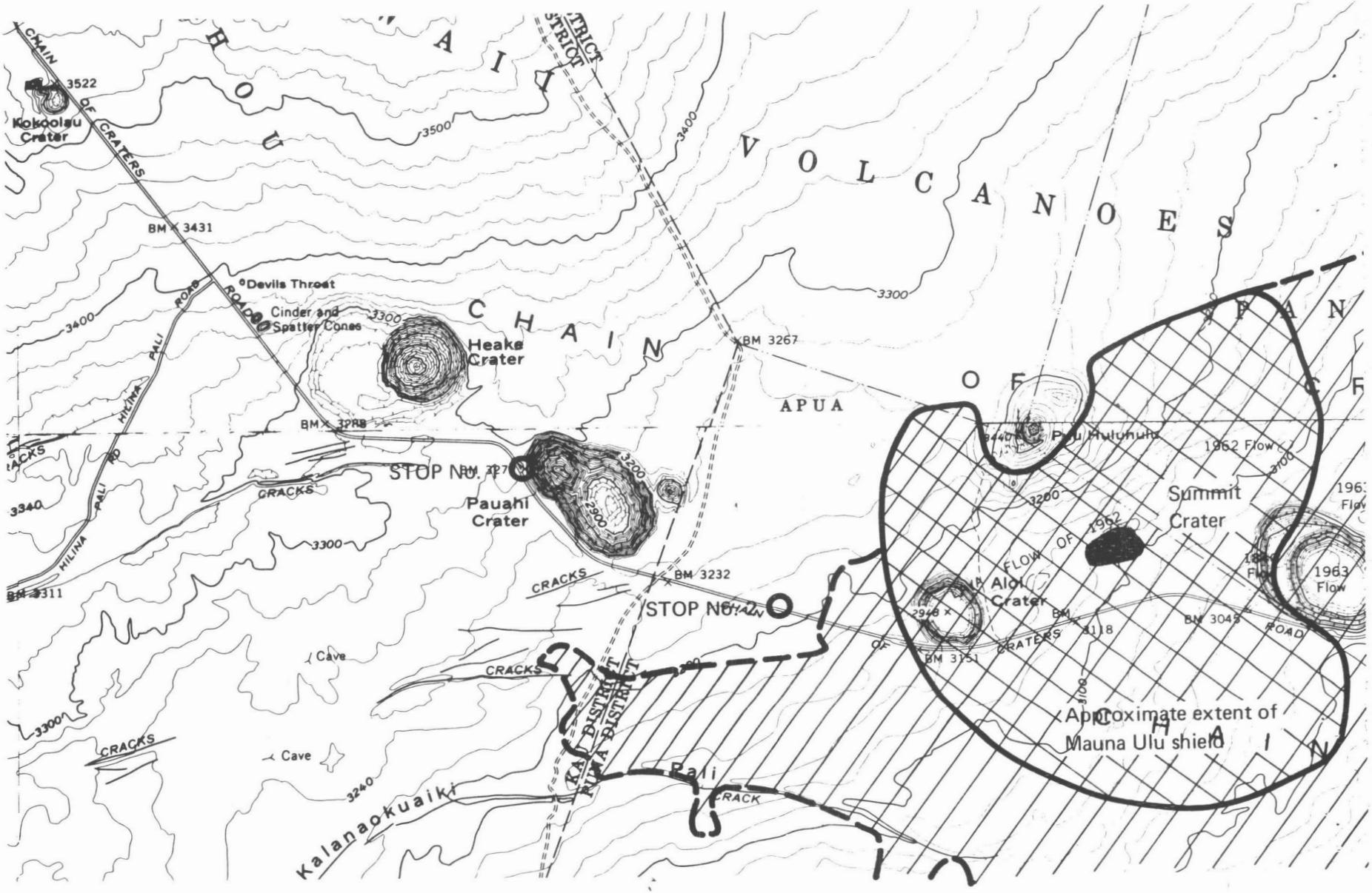
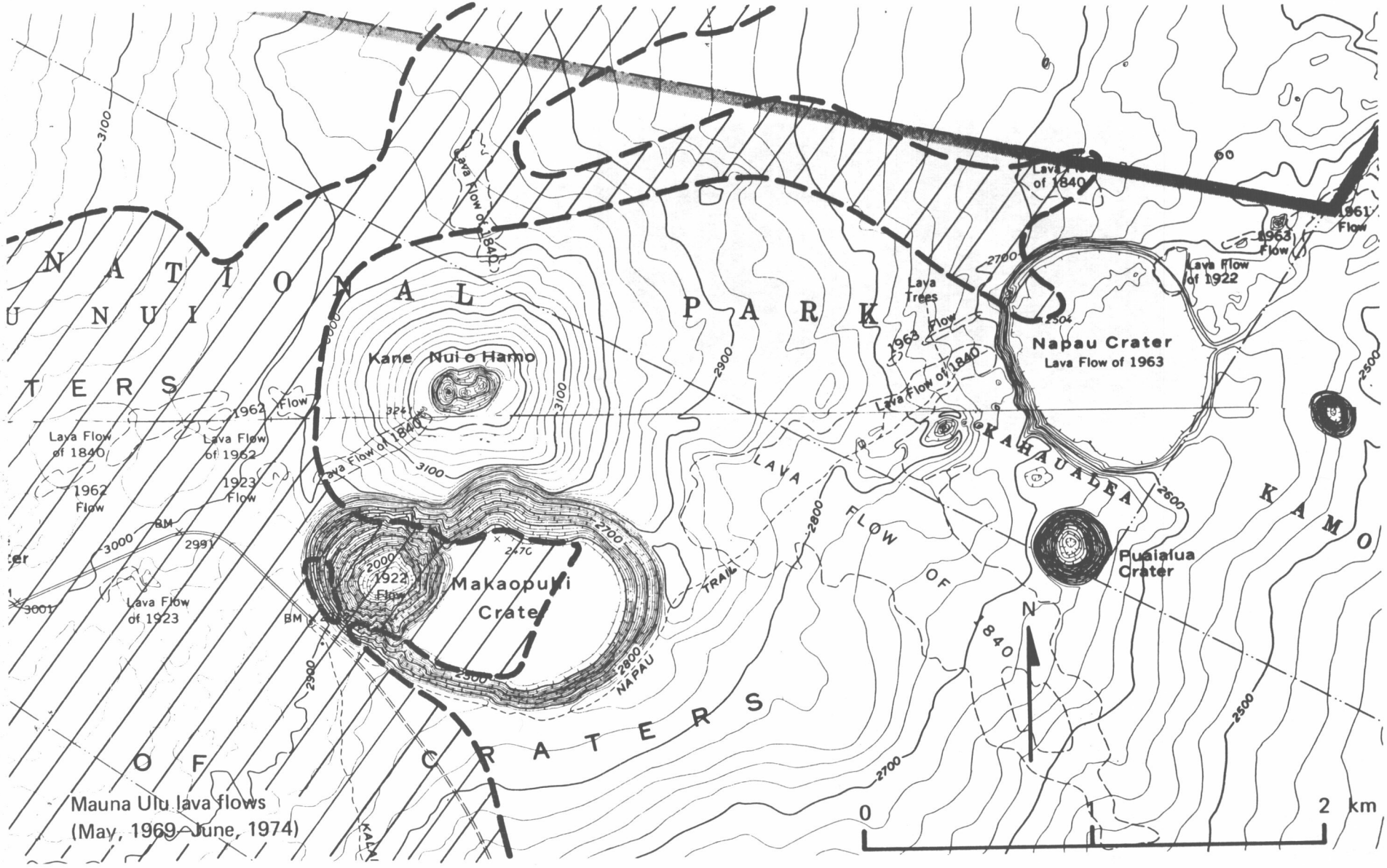


Fig. 9-8. Map of part of the Chain of Craters. (*Base maps of U.S. Geol. Survey 7-1/2' quadrangles Volcano, 1963, and Makaopuhi Crater, 1963.*)



Mauna Ulu lava flows
(May, 1969–June, 1974)

Fig. 9-9. Lava tree molds formed from the November 1973 eruption, near Pauahi Crater. (*Photograph by Ronald Greeley, University of Santa Clara, November 1973.*)

patterns form as surficial crust on moving flows and deform in response to movement of underlying melt. Near its source pahoehoe commonly forms billowed surfaces concealing large gas cavities. Walking on such flows can be treacherous. In general, as distance from the source vent increases and the lava loses more gas before final solidification, pahoehoe forms denser and firmer rocks that are easier to walk over. Other common characteristics of the flows on the flanks of Mauna Ulu are rock alteration zones and deposits of sublimated crystals, formed by prolonged action of volcanic gases escaping from the underlying cooling lava.

Mauna Ulu eruption: May 1969 to October 1971

On 24 May 1969, lava fountains broke out along an east-northeast-trending fissure extending from south of Pauahi Crater, through Aloi Crater, to north of Alae Crater. The fountains soon became localized along a fissure between Aloi and Alae Craters, the area in which the Mauna Ulu shield ultimately developed (Fig. 9-8). The ensuing activity that continued through December was characterized by a cyclic eruptive pattern in which brief episodes of strong activity and high fountaining were interspersed with extended periods of more subdued activity. During episodes of strong activity, lava fountains commonly attained heights as much as 400 m; the highest measured fountain was about 540 m. Alae Crater was almost filled with lava by August; it drained abruptly when cracks opened in its floor, and it was refilled by October.

During the first half of 1970, overflows from the fissure vent were common and built up a volcanic shield that by June was about 78 m high and about 1 km wide at its base. During this period, lava completely filled Aloi Crater. Beginning in July 1970, flows from vents to the east built a broad ridge on Mauna Ulu's east flank, and fed lava through tubes into the reservoir filling Alae Crater. This reservoir in turn fed sustained flows down Kilauea's south flank. Lava-tube systems developed in these flows that transported lava as pahoehoe many kilometers, and tube-fed pahoehoe reached the ocean in September 1970 and again in March to May 1971.

Throughout late 1970 and early 1971, a lava lake continuously occupied the Mauna Ulu summit crater, and collapse of the walls gradually enlarged the crater. Collapse extended to the vents along the east-flank, and a series of small pit craters formed that ultimately coalesced into a long trench down the east flank. In April 1971 the summit crater and the eastern trench merged into a single, elongated depression across Mauna Ulu. In May 1971, the eruptive activity at Mauna Ulu began to decline, flows gradually ceased, and the level of the lava lake steadily dropped. By mid-October, the molten lava had sunk out of sight, leaving a rubble-strewn crater floor about 145 m deep, and all eruptive activity had ceased.

Mauna Ulu eruption: February 1972 to May 1973

On 4 February 1972, lava quietly reappeared in the crater at Mauna Ulu. In a few days, lava rose to the level of the eastern trench and flowed down its rubbly floor, re-entered the tube leading to Alae, emerged within the gentle depression marking the site of the former crater, and filled it to overflowing. Lava soon filled the Mauna Ulu trench and summit crater, and repeated overflows covered new areas and further built up the Mauna Ulu shield to the east northeast.

In mid-March 1972 the brim-full lava lake at Mauna Ulu abruptly drained, and new vents opened both to the east and west. All but one of these vents was short-lived, but this one vent, within the northern part of the former Alae Crater, emitted lava for more than a year. Levees formed around the Alae depression and impounded a lava lake. Overflows from this lake gradually build a new volcanic shield that abuts the southeastern flank of Mauna Ulu. The Alae vent was connected to the main vent at Mauna Ulu by a lava tube, which sustained the lava lake. The Alae lava lake in turn fed long-lived flows throughout 1972 and the spring of 1973. Some of these flows poured into Makaopuhi Crater; they filled the deep west pit to the level of the east pit and covered most of the floor of the east pit. Lava flowing southward from Alae developed new systems of tubes, through which lava entered the sea during August-October 1972 and February-May 1973. Throughout this entire time, an active lava lake occupied the summit crater of Mauna Ulu.

Mauna Ulu and upper east-rift eruptions: May to December 1973

On 26 April 1973 an earthquake of magnitude 6.2 rocked Hawaii. This quake, though about 40 km deep and centered approximately 60 km north of Kilauea and having no connection with the magma supplying Mauna Ulu, may well have caused the subsequent drastic changes in volcanic behavior along the east rift zone. In the early morning of 5 May, strong harmonic tremor and rapid deflation of Kilauea's summit accompanied the complete drainage of the lava lake at Mauna

Ulu, leaving a dust-spewing, rubble-choked crater 200 m deep. Lava also drained from the Alae vent. About 4 hours later, fountains broke out uprift at Pauahi Crater, marking the first activity there in historic times. After about 2 hours, activity at Pauahi waned, but soon a new outbreak began along fissures farther uprift, within and near Hiiaka Crater, that lasted several hours. Two days after this eruption lava quietly returned to the crater at Mauna Ulu Moderate lava-lake activity gradually resumed, but on 9 June Mauna Ulu partly drained again. Although lava again returned to Mauna Ulu, the action became increasingly sluggish, and lava did not reappear at the Alae vent. The lava in Mauna Ulu rose gradually with time, but the surface area of actively circulating lava steadily diminished, and by mid-July the lake became nearly stagnant. In late September activity increased, and voluminous flows flooded the crater floor. In early November activity further intensified, lava fountains reached as high as 40 m, the lake surface reached the crater rim, and lava overflowed from the crater for several days. On 10 November, the Mauna Ulu lake drained abruptly and remained inactive for more than a month. This draining of the lava lake heralded the beginning of the eruptive activity centered at Pauahi Crater (see Section 2, Stop 1).

Mauna Ulu eruption: December 1973 to present (June 1974)

On 12 December lava quietly returned to Mauna Ulu's crater. Activity included mild spattering from a spatter cone and short-lived flows on the crater floor. As activity continued the spatter cone grew and repeated flows raised the floor of the crater, until in late January the spatter cone protruded above the crater rim and the floor had risen to just a few meters below the rim. On 24 January, activity increased greatly; fountains reached heights of 40 m, lava filled the crater, spilled over the brim, and flowed several kilometers. Activity declined after about 36 hours; Mauna Ulu had grown several meters in height. After a few quiet days, a second similar episode occurred, with fountains reaching 60 m and new flows covering wide areas. Several additional episodes of strong activity followed, each lasting from 12 to 36 hours and separated by 3-day to 5-week periods of relative quiet. During some eruptive episodes, fountains reached heights of 80 m; during others symmetrical dome fountains as high as 15 m developed. Flows reached as far as 9 km from the vent. In June Mauna Ulu had grown to a total height of 121 meters above its pre-1969 base. As of this writing, the same pattern of episodic activity continues.

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10. MAUNA IKI AND THE KA'U DESERT: KILAUEA VOLCANO, HAWAII

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Driving time to trail: 15 minutes from Park Headquarters
Hiking time: 3 to 3-1/2 hours, mostly over good trails. Rain gear, hiking boots, and drinking water recommended.

The Ka'u Desert lies southwest of Kilauea Volcano (Fig. 10-1). The region contains some of the most interesting and best preserved volcanic features found in the islands. The structural setting and synopsis of recent volcanic activity on the Ka'u Desert are discussed here, and a field guide to Mauna Iki is provided.

The major named landmarks for the part of the Ka'u Desert discussed here are shown on Fig. 10-2. Cone Crater (Fig. 10-3) and the adjacent Pit Craters (Fig. 10-4) on the Mauna Iki trail are especially interesting because of the spectacular depth and steepness of the pit walls. Puu Koae is a large complex of breached cones and is the source of a very large prehistoric flow extending nearly to the sea. Cone Crater, the Pit Craters, and Puu Koae are all features of the Koae fault system near the zone of intersection with the southwest rift zone. A fault scarp of the Koae system is shown in Fig. 10-5 at the point where the Mauna Iki trail crosses it. About 7 km southwest of the Pit Craters is the pair of "twin" cinder cones Kamakaiauka and Kamakaiawaena (Fig. 10-6), notable because of their near perfect symmetry and the general dearth of cinder cones on Kilauea Volcano.

STRUCTURAL SETTING

Ka'u Desert and vicinity is crossed by several systems of fractures and faults (Moore and Peck, 1965). Tens of meters of vertical displacement have occurred on the two major fault systems, and Kaoiki and Hilina, the former marking the structural contact between the Kilauea and Mauna Loa mountain masses. Located well within the body of Kilauea Volcano, the southwest rift parallels the Kaoiki system but intersects the summit caldera and its circumferential array of subsidence fractures. A fourth system, the Koae fracture system, shows vertical displacement with the northern blocks generally dropped down. The Koae fractures are typically open tensional cracks that are up to several meters wide.

The fracture system of the Southwest rift intersects Kilauea Caldera and its concentric faults near the summit. Several large cracks are exposed along the Crater Rim Drive on the southwest side of the caldera just before the road descends from the caldera rim to the floor. In September 1971 an eruptive fissure cut across the road at this locality and lava spread outward in very thin sheets. Figure 10-7, an aerial view including Halemaumau, shows the system of cracks and the 1971 lava after the road had been rebuilt. There is a small parking area on the road where the 1971 lava interrupted it and a brief hike to the southwest of this point is worthwhile. Figures 10-8 and 10-9 show preexisting southwest rift cracks with spatter inside and on the edges from the 1971 eruption. These two photographs show only Kilauea pyroclastic beds which resulted chiefly from the 1790 eruption; the thinly bedded depostis are approximately 3 m thick in this region and are underlain by interbedded basaltic lava and pyroclastics. Some of the deeper cracks cut into the lavas, exposing them to view. During the 1971 eruption, some new cracks formed here as the sources of fountains, and some older cracks opened further with new lava emanating from them. Figure 10-10 shows a new vent that was the source of fountains early in the 1971 eruption. Abundant spatter and evidence of local drainback are characteristic of fountain vents in Hawaii.

HISTORIC ERUPTIONS IN THE KA'U DESERT

The historic lavas of the Ka'u Desert rest on basalts and tuffs of Kilauea and presumably Mauna Loa volcanoes. A generalized cross section is shown on the geologic map of the Ka'u Desert quadrangle by Walker (1969) together with a thorough discussion of the bedrock and mappable units. See also the extensive discussions by Stearns and Clark (1930), Stearns and Macdonald (1946), and Macdonald and Abbott (1970).

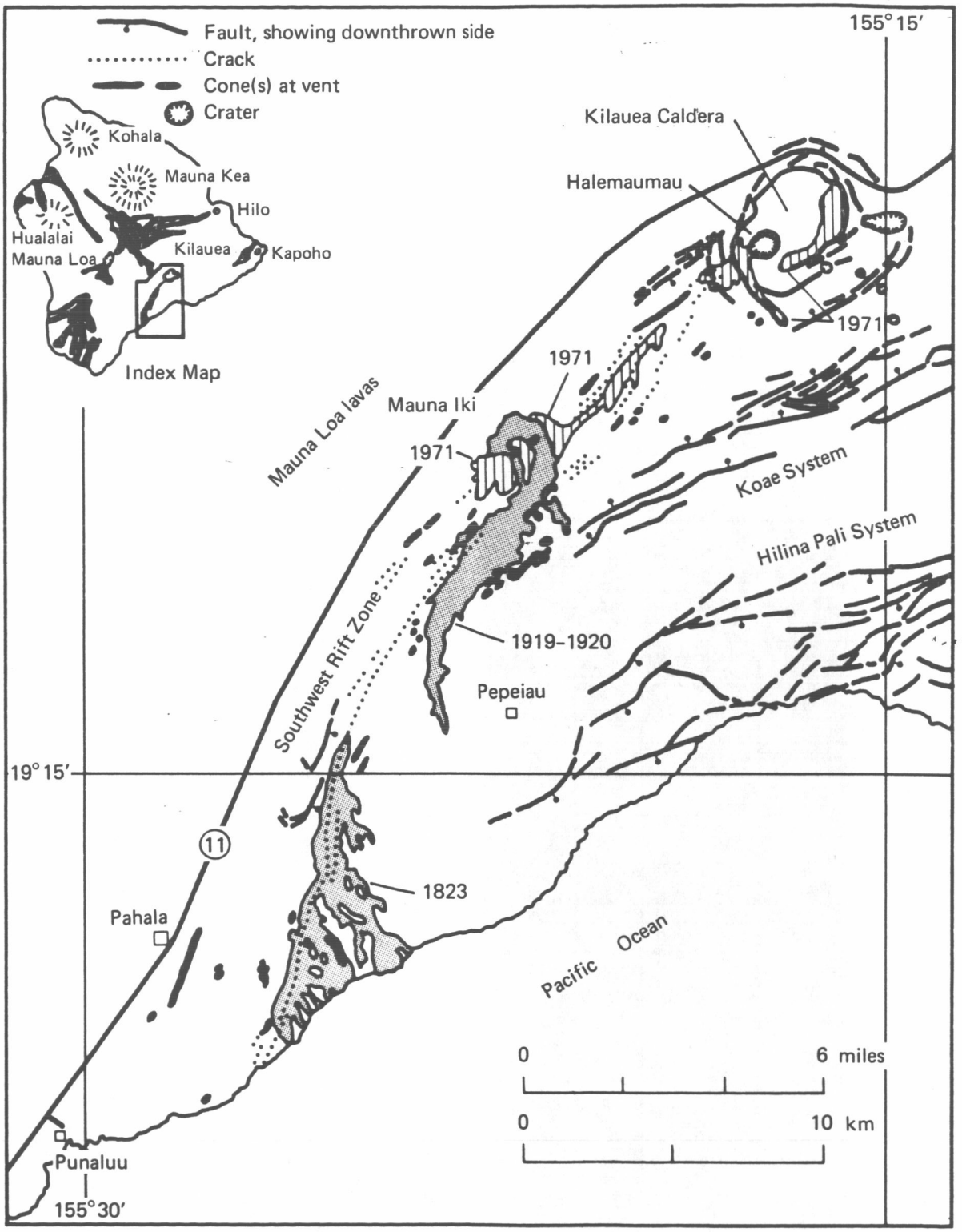

Fig. 10-1. Sketch map of the southwest flank of Kilauea Volcano, based on a map by Macdonald and Abbott (1970) with additional information from Walker (1969) and unpublished data from the U.S. Geol. Survey-Hawaiian Volcano Observatory.

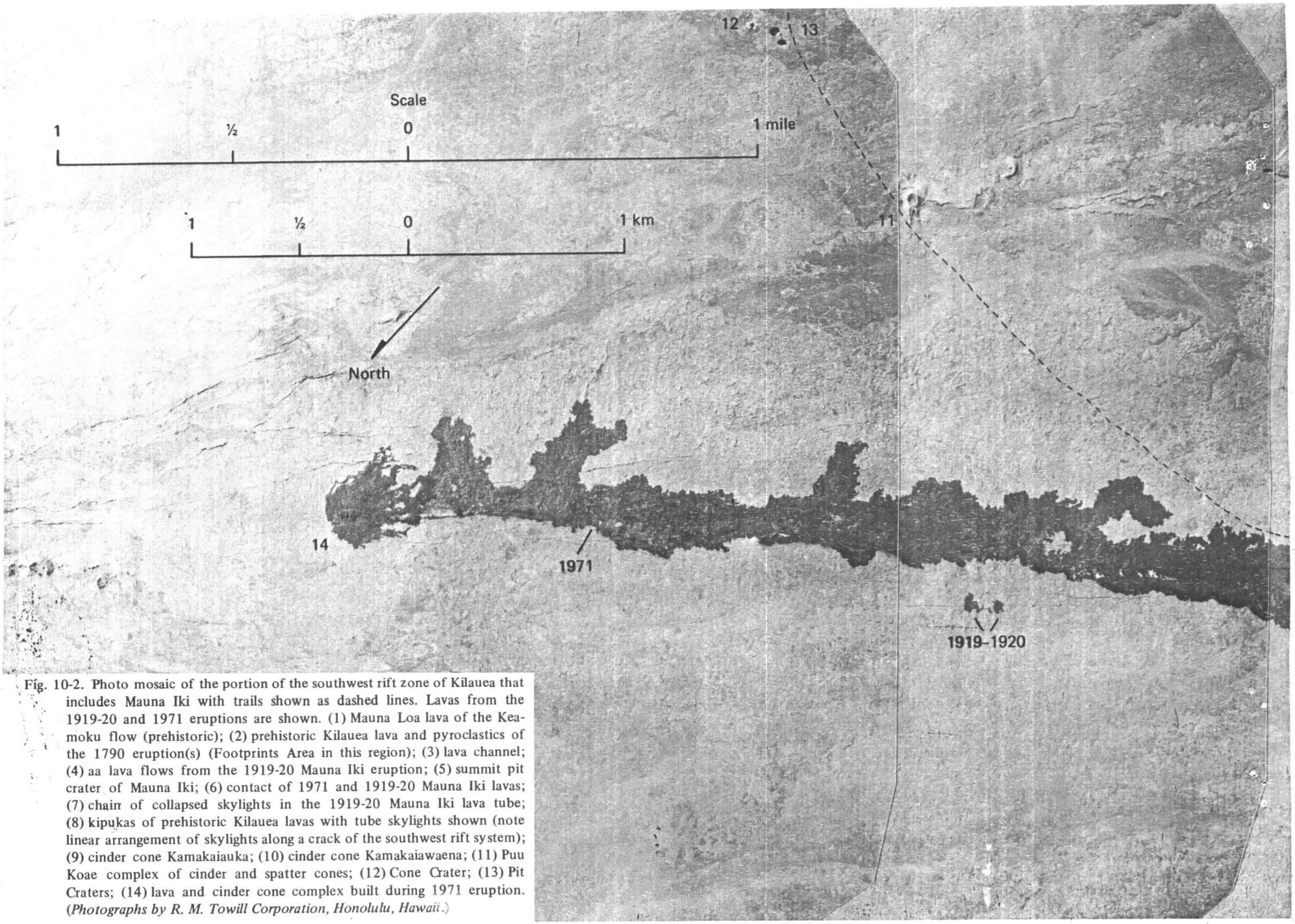

Fig. 10-2. Photo mosaic of the portion of the southwest rift zone of Kilauea that includes Mauna Iki with trails shown as dashed lines. Lavas from the 1919-20 and 1971 eruptions are shown. (1) Mauna Loa lava of the Keamoku flow (prehistoric); (2) prehistoric Kilauea lava and pyroclastics of the 1790 eruption(s) (Footprints Area in this region); (3) lava channel; (4) aa lava flows from the 1919-20 Mauna Iki eruption; (5) summit pit crater of Mauna Iki; (6) contact of 1971 and 1919-20 Mauna Iki lavas; (7) chain of collapsed skylights in the 1919-20 Mauna Iki lava tube; (8) kipukas of prehistoric Kilauea lavas with tube skylights shown (note linear arrangement of skylights along a crack of the southwest rift system); (9) cinder cone Kamakaiauka; (10) cinder cone Kamakaiawaena; (11) Puu Koae complex of cinder and spatter cones; (12) Cone Crater; (13) Pit Craters; (14) lava and cinder cone complex built during 1971 eruption. (*Photographs by R. M. Towill Corporation, Honolulu, Hawaii.*)

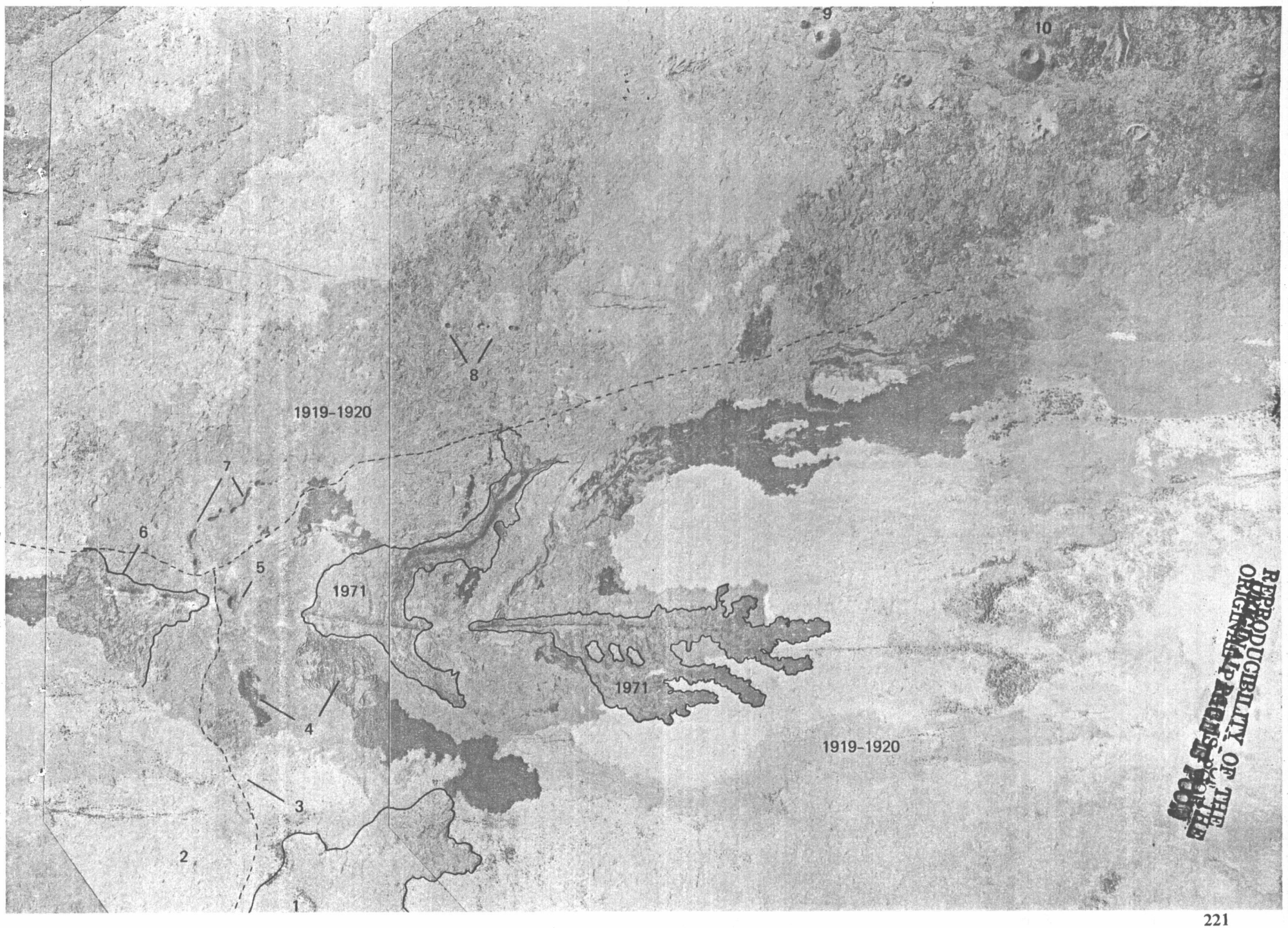

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Fig. 10-3. Cone Crater viewed across one of the two pit craters. This cone has a very deep pit in the top, probably extending to the same depth as the floors of the two pit craters (*Photograph by author, October 1967.*)

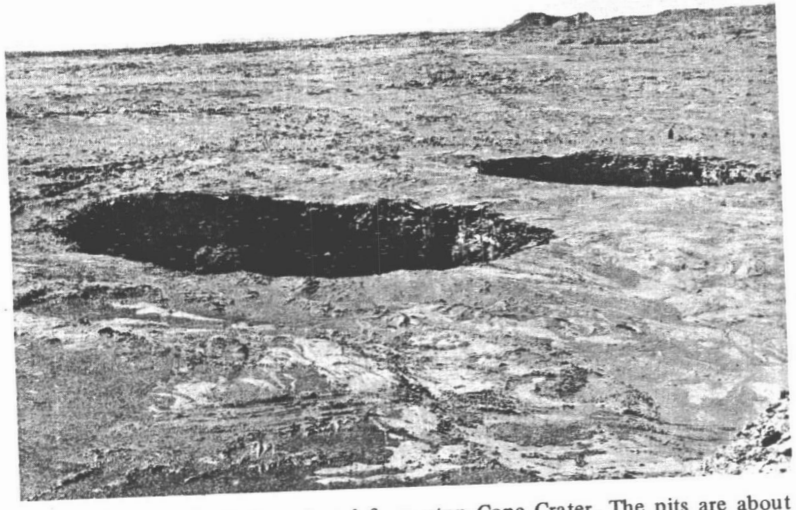

Fig. 10-4. Two Pit Craters viewed from atop Cone Crater. The pits are about 30 m in diameter, greater than 50 m deep, and are connected below by a large lava tube. Puu Koae is on the horizon, right of center. (*Photograph by author, October 1967.*)

Fig. 10-5. Fault scarp of the Koae fault system at a point where the Mauna Iki trail crosses. In the foreground, the scarp is gradual, but in the background it is a cliff with about 10 m vertical displacement. The gray sand right of the fault scarp is an exposure of Kilauea pyroclastics seen here and elsewhere in profusion in the Ka'u Desert. (*Photograph by author, October 1967.*)

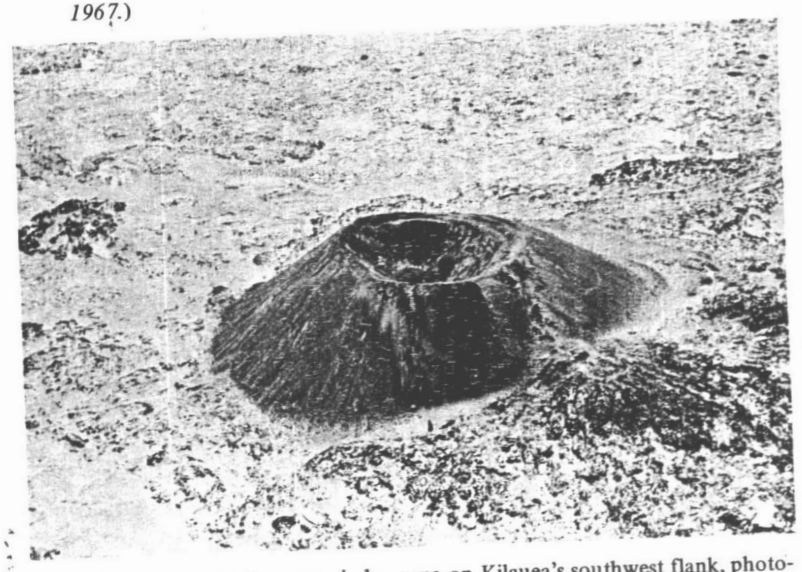

Fig. 10-6. The Kamakaiawaena cinder cone on Kilauea's southwest flank, photographed from the air. The cone stands about 50 m above the surroundings. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

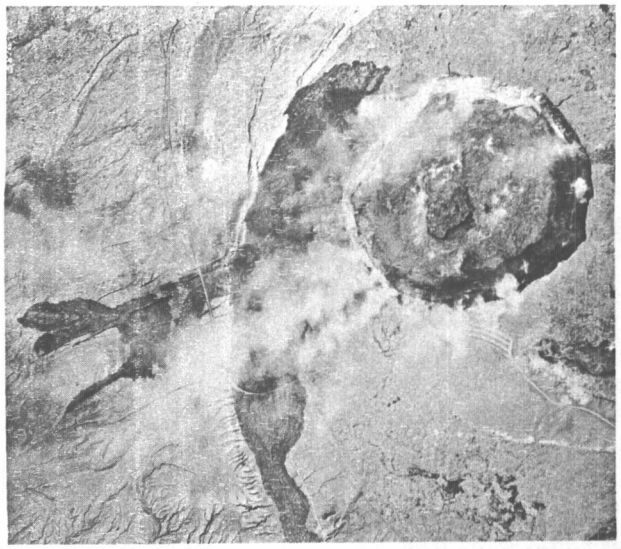

Fig. 10-7. Vertical aerial view of Halemaumau and the southwest rim of Kilauea Caldera, showing the cracks of the southwest rift system and lava erupted in September, 1971. When this photograph was made in October 1972, the road had been repaired following its destruction by the eruption. (*Photograph by R. M. Towill Corporation, Honolulu, Hawaii.*)

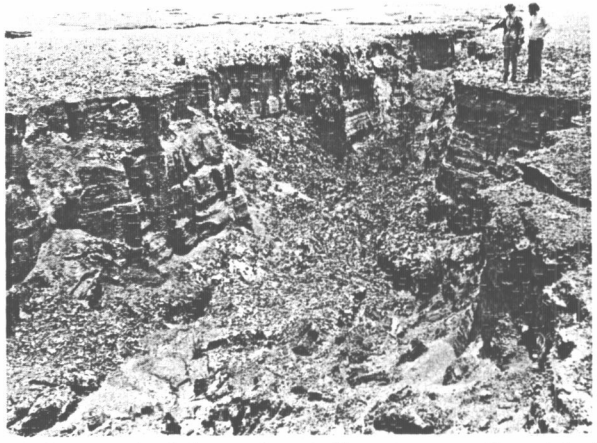

Fig. 10-8. A large crack of the southwest rift system near the point of intersection with the Kilauea Caldera rim. The surface deposits consist of thin lava sheets and spatter from the September 1971 eruption. Thin beds of Kilauea pyroclastics, chiefly erupted in 1790, are seen in section, with the new materials draped over. (*Photograph by author, May 1974.*)

Fig. 10-9. Lava and spatter from the September 1971 eruption draped over and pasted on the walls of an old crack of the southwest rift zone near the rim of Kilauea Caldera. (*Photograph by author, May 1974.*)

Fig. 10-10. A new vent created during the September 1971 eruption on the Kilauea Caldera rim along fractures of the southwest rift zone. Bits of spatter are seen in abundance as well as partial drainback of lava into the roughly circular pit. This pit occurs at the end of a long crack (seen in the lower right). (*Photograph by author, May 1974.*)

One of the first eruptions of Kilauea Volcano witnessed and recorded by western men was the 1823 eruption on the southwest rift zone (Fig. 10-1). It was a voluminous eruption (11.5×10^6 m^3) of low-viscosity lava that poured into the sea, overpowering Hawaiian residents on the coast (Stearns, 1966, p. 134). The next eruption on the southwest rift zone occurred in 1868, simultaneously with an eruption on Mauna Loa. Stearns (1966, p. 136) noted that lava rose in a fissure 1 m wide and 2.4 km long, forming nine small patches on the surface and four driblet spires. A dike was formed where the lava did not pour out of the fissure and can still be seen along the lower southwest rift zone (Stearns and Clark, 1930).

The next recorded activity on the Ka'u Desert began on 15 December 1919 with the opening of old and new fissures at several points along the southwest rift zone. Mauna Iki is a small shield built during these eruptions of mostly vesicular pahoehoe during 1919 and 1920. The following narrative of the 1919-20 eruption is from Jaggar (1947, pp. 139ff).

Two days before the outpouring on the rift zone, activity began inside Kilauea Caldera as large fuming cracks opened up adjacent to the then small-diameter (about 425 m by 360 m) Halemaumau crater with its continuously active lava lake. On 15 December 1919, however, cracks opening along the southwest rift zone indicated the lateral motion of subsurface lava, "splitting the mountain apart" (Jagger, 1947, p. 137). In a few days, Halemaumau drained completely of liquid lava (some was erupted on the surface of the caldera floor), refilled, and then drained again on 23 December. During this period, lava erupted in three places in Ka'u along the rift zone. The second of these sites, called the "six-mile outflows" by Jaggar (1947, p. 139), became Mauna Iki. Jaggar described the outflow as that from a dike which had reached the surface.

The third site, 14.5 km down the rift zone, was also vigorously active, but the six-mile outflows increased as the others diminished. In the last days of December 1919, the major flow at Mauna Iki was formed. It started as pahoehoe at its source, but changed to aa and progressed about 3 km per day. In the third week of January, the flows at the six-mile source built up the mound that is now Mauna Iki. Three lava pools formed at Mauna Iki, and the remains of at least one can be seen in the summit pit of the mound. Jaggar likened the mound at Mauna Iki to a miniature Mauna Loa; its lateral dimensions are about 1.5 km (wide) by 3 km (length downslope).

Over the next few months, Mauna Iki continued to grow, but laterally instead of vertically. Jaggar (1947, p. 143) considered that it has a critical height of about 40 m above which it could not grow; additional lava supplied from the fissures below would result in failure of the flanks of the mound, causing horizontal flows. Massive diffusions of lava continued at Mauna Iki through April 1920, pouring through lave tubes in all directions. Throughout this period, Halemaumau was continuously active with large variations in the level of the lava lake. In June, Jaggar observed fountaining activity on a small lava lake in the summit of Mauna Iki, noting that it alternately crusted over and fountained explosively, while flows continued in the main tube to the east, south, and elsewhere on the flanks of the shield.

In August 1920, eight months after the beginning of the eruption, the flows at Mauna Iki stopped as Halemaumau rapidly filled as though the underground conduits from the Kilauea summit to the southwest rift had closed, preventing downslope escape of lava. The total outpouring of lava in the 1919-20 eruption was 48×10^6 m^3 (Stearns, 1966, p. 140). Jaggar (1947) gives several interesting photographs of the Mauna Iki activity, including a view of the summit pit nearly filled with pahoehoe (plate 39, p. 465).

Fifty-one years elapsed between the end of the 1919-20 eruption and the next effusion of lava on the surface in the southwest rift zone. Fissures opened on the caldera floor southwest of Halemaumau on 24 September 1971, following several weeks of inflation of the summit region and mild earthquakes in the Kilauea summit area and near the Koae fault system in the Ka'u Desert. Fountains 50 m high played from the new vents, sending lava laterally across the caldera floor and into Halemaumau. A vent soon opened in the crater itself. Within 40 min of the onset of this eruption, cracks of the southwest rift system opened in the western end of the caldera. Fountains began here, crossing the crater rim drive and the caldera wall, slowly moving southwest as the fissures progressively opened downslope. The fountaining fissures opened to the northwest, too, crossing Halemaumau and extending into the central caldera floor. The lava that emanated from the fissures southwest of the caldera rim were of very low viscosity as evidenced by the thin continuous sheets left after the activity subsided. The extent of the lava deposits near the caldera rim is seen in the aerial photograph (Fig. 10-7).

Observers from the Hawaiian Volcano Observatory watched the line of fountains migrating down the southwest rift zone, extending southwestward and gradually extinguishing at the northeast end, with the line of fountains no more than about 150 m long at any given time. They noted the opening of new cracks and the widening of existing cracks; fume and spontaneously combusting gas first rose from the fissures, followed by mildly explosive ejection of blobs of lava, shot to a height of a few meters. Some tens of meters behind the spray of lava blobs, the fissure fumed violently and then gave way to full lava fountaining. Diminution of activity at the trailing end of the fissure occurred as fountaining subsided to spatter vents and then to roaring gas vents. The fountaining in this phase of the eruption stopped three hours after it began.

About 11 hours later, on 25 September 1971, the eruption resumed at a point on the southwest rift zone about 2.5 km below the lowest vent of the opening phase. Cracks in the rift zone continued to open preceptibly even where lava did not emanate. Where lava did erupt in fountains, the fissures opened and developed as had been observed the previous night near the summit. While much lava poured laterally in new surface flows, great volumes cascaded into other deep cracks, and in some cases into old lava tubes. About three hours after it began, this phase of eruption ceased, leaving a nearly continuous line of vents along a single surface fissure 1.6 km long. During the night of 25 September, the floor of Halemaumau was subsiding, and observers standing on the rim could hear a continuous succession of rock slides and avalanches.

The next morning, 26 September, a new outbreak of fountaining occurred, this time on the southwest flank of the Mauna Iki shield. The fissure progressively opened downslope as had been seen before. Within two hours yet another fissure opened, but this time upslope, northeast of Mauna Iki and encroaching on the Iki shield. Activity migrated upslope toward the summit of Kilauea, and by evening the fissure on the northeast slope of Mauna Iki had stopped fountaining and was emitting large and luminous flames 1–2 m high, as well as copious steam and SO_2 gas. Here, spectroscopic observations of the flames were made on the night of 26 September (Cruikshank *et al.*, 1973) after the observers had hiked from the highway along the Mauna Iki trail by the light of nearby active lava fountains (further to the northwest of Mauna Iki).

Lava effusion and mild fountain activity persisted along the fissures between Mauna Iki and Kilauea caldera until late on 29 September and then ceased as seismic activity also quieted down. Lavas of varying thickness from the 1971 eruption cover 4 km^2. By the end of the 1971 southwest rift eruption, the central floor of Halemaumau had dropped 45 m from the previous level, corresponding to a volume decrease on the order of 18×10^6 m^3.

FIELD TRIP TO MAUNA IKI AND THE SITE OF THE SEPTEMBER 1971 SOUTHWEST RIFT ERUPTION

The eruptions on the southwest rift zone in 1823, 1868, 1919-20, and 1971, as well as prehistoric eruptions, have left an impressive array of the various features typical of Hawaiian volcanoes. This guide considers primarily the Mauna Iki region, a product of one major eruption that was then modified by another eruption 51 years later. Though activity on the southwest rift zone is far less frequent than that on Kilauea's east rift zone, the region considered here is an active volcanic zone bearing close study in conjunction with eruptions and deformation elsewhere on Kilauea Volcano.

Mauna Iki is easily reached by a good trail which originates on Highway 11, 14.7 km (9.1 mi.) southwest of the Hawaii Volcanoes National Park Headquarters. The roadside turnout is about 70 m beyond the Hilo 39 m milepost, and there is adequate parking space for several cars. The trail that begins here is the Mauna Iki Trail, which also passes the Footprints Area (1.3 km) and intersects the Ka'u Desert Trail

(2.9 km) that runs roughly southwest-northeast. The Mauna Iki Trail continues east across the Ka'u Desert past Puu Koae, the Pit Craters (9.2 km, Fig. 4), and Cone Crater on to the Hilina Pali Road (13.9 km). The entire trail is a fascinating hike and is highly recommended.

Mauna Loa Lavas. The Mauna Iki trail begins on the Keamoku lavas, a prehistoric aa flow originating on the flank of Mauna Loa. About 15 m from the origin of the trail, a deep ditch is crossed by a wooden bridge. Left of the bridge are slickensides in the lava ("grooved lava"), resulting from the drag of plastic lava across more solid protrusions, similar in form to slickensides seen in glacial terrain. All across the aa flow are large accretionary lava balls: meter-diameter spheroids formed by accumulation of successive layers as a nuclear fragment is transported along the still viscous lava. Accretionary lava balls are common elsewhere, such as on the 1823 southwest rift flow (Macdonald and Abbott, 1970, p. 72 and Figs. 19 and 72). Figure 10-11 shows an especially well-formed ball with the outermost layer broken away to reveal the interior.

The trail drops 6 to 9 m off the Keamoku aa flow edge to the smooth pahoehoe flows of Kilauea about 825 m from the road where there are large irregular deposits of dark dune sand, which are part of the extensive pyroclastics from Kilauea eruptions, largely the 1790 event. The Kilauea flows here show many well-preserved ropes and wrinkles common to low-viscosity pahoehoe lavas.

Foot Prints Area. The Mauna Iki trail soon forks to the left, while the right-hand branch (asphalt surfaced) goes 320 m to the Footprints Area. This area merits a side trip to see the preserved footprints of 18th century Hawaiian warriors who were caught in a devastating and unusual eruption of Kilauea in 1790. A brief account of the event is given by Macdonald and Abbott (1970, pp. 70–71). A more detailed discussion with a new and appealing interpretation has been formulated by Swanson and Christiansen (1973), who believe that the warriors and their entourage were killed not by an ash flow (very rare in Hawaiian volcanoes) but instead by a base surge accompanying explosions in Kilauea Caldera. Footprints are found in two layers of ash separated by 90 cm of dune sand (which is found drifted throughout the area; Fig. 10-12).

Fig. 10-11. C. B. Pilcher and a 2-m accretionary lava ball on the Keamoku lava flow (Mauna Loa) along the trail to Mauna Iki. The outer layers of the ball have been broken open to expose the interior. (*Photograph by author, May 1974.*)

Fig. 10-12. Two layers of ash from the 1790 eruptions, with a thick layer of gray pyroclastic sand between. The footprints of ancient Hawaiian warriors occur in these two layers of ash, presumably caused by a base surge from explosions in Kilauea Caldera. (*Photograph by author, May 1974.*)

A base surge is a "ring-shaped basal cloud that sweeps outward as a density flow from the base of a vertical explosion column" (Moore, 1967). Base surges are recognized in shallow underground nuclear explosions as well as in violent volcanic eruptions (Moore, 1967). No fully developed base surges have been observed at Kilauea since the phenomenon was recognized, but photographs of the steam explosions at Halemaumau in 1924 show signs of incipient base surges. As Swanson and Christiansen (1973) note, base surges travel at velocities of 20 to 30 m/sec and can extend many kilometers from the source. They are most commonly associated with phreatic or hydromagmatic eruptions, and while some surface deposit is usually left behind, the surge may carry only water and gas, leaving no detectable surface manifestation of the event.

Quoting from Swanson and Christiansen (p. 85), "The phreatic and hydromagmatic nature of the Kilauea (1790) eruption is indicated by the abundant lithic ejecta and chilled juvenile material, by the chilled and fractured surface characteristics of the ejecta fragments, and by analogy with the closely observed steam blasts at Kilauea in 1924. Much of the ejecta was incandescent, judging from native accounts, indicating a temperature $> 500^{\circ}C$."

Several of the preserved footprints are protected in enclosures installed by the Park Service, but the shifting sands occasionally uncover other footprints in the area. The layers of yellow ash in which they are formed are only a few centimeters thick and rather fragile.

Footprints Area to Mauna Iki. Return to the trail junction of the Footprints Area and Mauna Iki. The trail to Mauna Iki beyond the fork is marked by two parallel rows of rocks and is easily followed across the Kilauea lavas to the Mauna Iki shield. Many interesting morphological features can be observed along the trail, including the various forms of pahoehoe lava. Large lava tumuli occur here in profusion (Fig. 10-13). Often the tumuli have squeeze-ups of lava visible in the medial fractures, and in some cases the lava has poured out forming long entrails and toes of pahoehoe.

The trail from the Footprints Area to the summit of Mauna Iki passes a small aa lava flow from the 1919-20 eruption. A few hundred meters southwest of that small flow on the flank of the shield is a large collapsed zone which is the origin of a major aa flow on the west side of Mauna Iki. It appears that drainage of lava from an elliptically shaped pocket on the flank of the shield caused the surface to slump in a jumble of partly intact blocks, aa, and pahoehoe lava.

Fig. 10-13. N. D. Morrison and a large tumulus in prehistoric Kilauea lavas between the contact with the Mauna Loa and Mauna Iki lavas, along the Mauna Iki trail. Most of the tumuli here are fractured. Although this one has no secondary lava squeeze ups in its center, many in the area do. (*Photograph by author, May 1974.*)

Clusters of golden brown glassy filaments of lava known as Pele's hair are found in profusion in cracks in the rocks all across the Ka'u Desert. These filaments form in lava fountains and are windborne for several kilometers. Much of the hair on and around Mauna Iki resulted from the fountain eruptions of September 1971.

Shortly before the contact with Mauna Iki lavas is reached, the trail crosses a broad but shallow lava channel in Kilauea pahoehoe. The floor of the channel (Fig. 10-14) is a finely textured lava surface with the long axis of drawnout ribbons elongated in the direction of flow. The small scale of the texture suggests a flow of relatively low viscosity and fairly high velocity. The channel is terminated by overfilling by Mauna Iki lavas. Flow surges in the channel caused overflow of the natural levees in several places near the point where the trail crosses.

1919-20 MAUNA IKI FLOWS

Progessing along the trail, Mauna Iki flows of 1919-20 are encountered. The contact with the underlying prehistoric Kilauea flows

is most easily recognized by the abrupt change in vegetation density, mostly of the scrubby Ohia trees. Mauna Iki lavas are black scoriaceous pahoehoe with local areas of aa and broken up pahoehoe. Phenocrysts of olivine and plagioclase are present locally, as are lobate toes of dense basaltic glass (Walker, 1969). From the contact with Mauna Iki lava, the trail begins the easy climb to the summit area, about 38 m above the base of the shield. To the right of the trail is an enormous tumulus, a few tens of meters distant.

The trail passes a few meters to the left side of the circular pit near the summit and then on to a trail intersection marked by three signposts. The summit pit, shown in Fig. 10-15, is breached by a short section of a collapsed east-west lava tube, and the thinly layered lavas making up the Mauna Iki shield are exposed in the walls. The tube extending east and then south from the summit pit is extensive and is discussed below.

Mauna Iki Summit. The trail crossroad at the summit is a good vantage-point from which to note the local geographical features. Due south stand the two cinder cones Kamakaiauka and Kamakaiawaena; east are Cone Crater and Puu Koae. Immediately northeast are the steaming fissure vents of the 1971 eruption. The line of steaming vents rides up part way onto the Mauna Iki shield and is easily accessible on foot.

From the trail intersection, points of nearby interest are: *To the south*, Kipuka Pepeiau (11.8 km) and Hilina Pali Road (19.6 km); and *to the northeast (toward Kilauea)*, Mauna Iki Trail (1.1 km), Hilina Pali Road (11 km), and Volcano Observatory (12.6 km). Kipuka Pepeiau is approximately the southernmost point on the Ka'u Desert trail, whence the trail turns east back to the Hilina Pali Road. From the summit of Mauna Iki, the trail to the Pit Craters is 6.3 km.

From the summit of Mauna Iki, visitors may wish to explore a variety of features in the immediate area. Of particular interest are (1) the large lava tube emanating from the summit pit and collapsed in several sections, (2) the fissures that were the source of the 1971 lavas both to the northeast and southwest of Mauna Iki, (3) the aa flows from the flanks of the Mauna Iki shield, and (4) the summit pit.

Large collapsed roof sections of the Mauna Iki lava tube have exposed an interesting feature of this shield. The tube extends east from the summit pit and then turns south where the largest collapses are found. The width of the tube is a few tens of meters in places and, though the floor is largely covered with breakdown, some idea of the enormous size can be gained from the edges of the collapse openings.

Fig. 10-14. Lava channel in the Kilauea prehistoric lavas along the trail to Mauna Iki. The Mauna Iki shield is left of center on the horizon with the trail (marked by parallel rows of rocks) leading toward it. The direction of flow in this channel was away from the camera. Deposits of windblown gray sand accent the fine elongated texture of the channel floor. (*Photograph by author, May 1974.*)

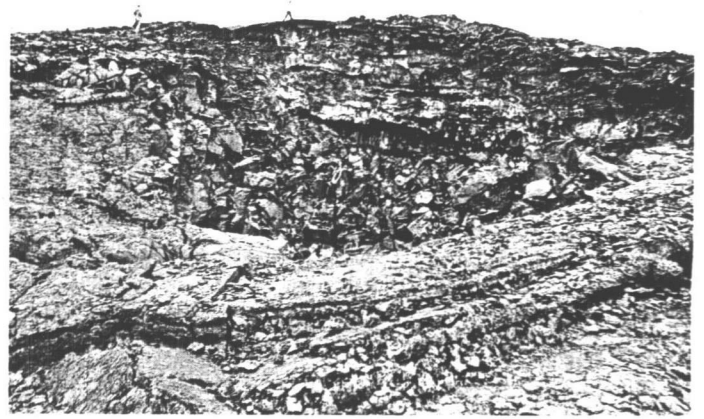

Fig. 10-15. The summit pit crater of Mauna Iki seen with an ultra wide-angle lens. This pit was filled with liquid lava during much of the 1919-20 eruption (compare with Jaggar, 1947, plates 38 and 39). (*Photograph by author, May 1974.*)

This lava tube, together with a few others, was active throughout the nine months of lava effusion at Mauna Iki in 1919-20. Though it was possible to enter parts of the tube through broken-down roof sections as early as mid-1921, the inner reaches remained hot for several years. The trace of the tube shows on aerial photographs (Fig. 10-2); Fig. 10-16 is a wide-angle view of one of the elongated collapsed sections seen from the ground. The tube can be entered through one of the skylights (Fig. 10-17), but the lava is sharp and the unstable jumbled blocks require considerable caution. Abundant deposits of white sulfates are found in protected nooks in the tube. The collapsed sections of the tube give a good sectional view of the upper several meters of the Mauna Iki lavas, most of which were deposited in thin (a few tens of cm) flows typical of the shield-building process in Hawaiian volcanoes. Some sections of the Mauna Iki tube collapsed before the activity of 1919-20 ceased, as indicated by drainage of a surface flow from the same eruption into a small skylight (Fig. 10-19).

The general question of lava-tube formation in Hawaiian volcanics is discussed by Greeley (1971, 1972), Cruikshank and Wood (1972), and Peterson and Swanson (1974).

About 1.6 km south of the Mauna Iki tube is a chain of skylights in a prehistoric tube lying in an elevated ridge oriented parallel to the southwest rift. From aerial photographs, the tube appears comparable in size to the Mauna Iki tube.

1971 Eruption. Vents of the 1971 eruption northeast of Mauna Iki and partly encroaching on the flanks of the shield are easily reached by a short hike from the summit. The vents are typical of Hawaiian eruptive fissures, showing the smooth lava coating, usually stained red and sometimes yellow from sulfur deposits. In addition to the major flows that emanated from these vents, the ground for meters in either lateral direction is peppered with hand-sized and larger pieces of spatter that fell from the lava fountains, solidifying shortly after contact. The vents to the northeast are of interest but considerably less impressive than those on the southwest flank of the Mauna Iki shield.

About 366 m southwest of the summit pit is the beginning of a very deep fissure that was a source of 1971 lava fountains 15 to 20 m high. There also is a very deep crack in the Mauna Iki shield parallel to, and then joining, the line of vents. This crack appears to be new, or at least it was widened considerably by the 1971 eruption. The crack and the fissure are at least 15 to 18 m deep in places. All along the fissure are new lavas, spatter, and evidence of partial drainback into the vents

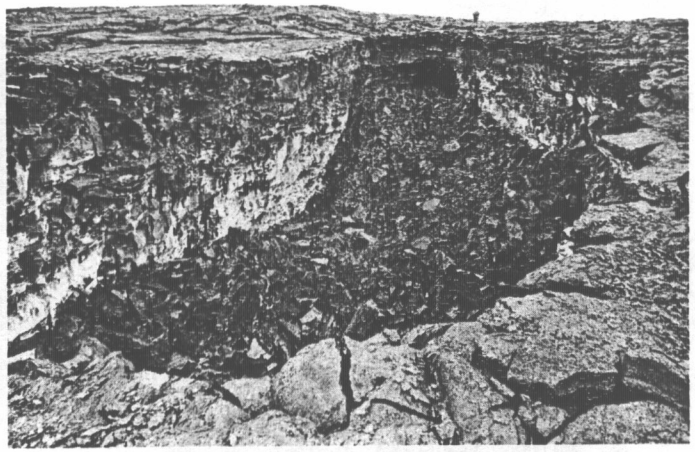

Fig. 10-16. Wide-angle view of an elongate skylight in the main lava tube at Mauna Iki (point 7 in Fig. 10-2). Figures behind umbrella on the horizon provide the scale. Thin pahoehoe sheets of lava are exposed in the section. (*Photograph by author, May 1974.*)

Fig. 10-17. Oblique aerial view southward along the partly collapsed lava tube of Mauna Iki. (*Photograph by Ronald Greeley, University of Santa Clara, June 1974.*)

Fig. 10-18. Two skylights in the Mauna Iki tube with a natural bridge separating them. Entrance to the tube is hindered by unstable rock. (*Photograph by author, May 1974.*)

Fig. 10-19. Lava stalactities in the Mauna Iki tube. See also Jaggar, 1947, plate 41. (*Photograph by author, May 1974.*)

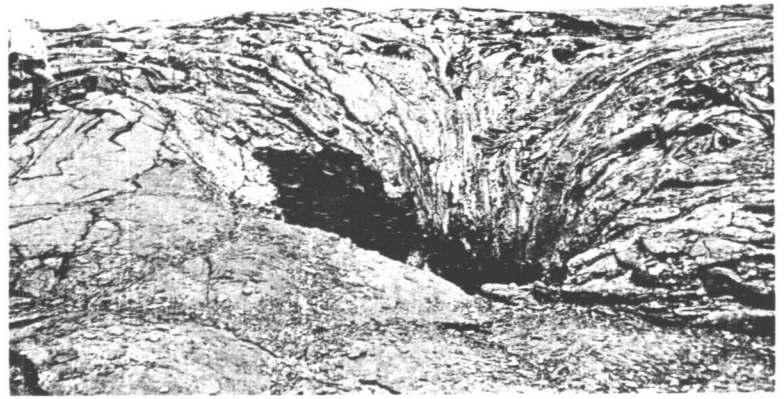

Fig. 10-20. Drainback of 1919-20 lava into the Mauna Iki tube. (*NASA-Ames photograph by Ronald Greeley, 1970.*)

on the southwest flank of the shield. Some vents are still steaming and exhaling hot drafts as of mid-1974, three years after the eruption. The vents on the lower side of Mauna Iki were the sources of considerable new lava, most of which ran off in a wide channel to the south.

ACKNOWLEDGMENTS

I thank the staff of the Hawaiian Volcano Observatory, particularly D. W. Peterson and R. T. Holcomb, for providing detailed information on the September 1971 eruption to supplement my field notes. R. Greeley provided valuable suggestions in the field. Supported in part by NASA Grant NGL 12-001-057 and by Air Force contract F19628-71-C-0008.

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11. KAUMANA LAVA TUBE

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11. KAUMANA LAVA TUBE

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Driving time from downtown Hilo: 15 minutes
Hiking time, roundtrip through tube: 2-1/2 hours

The entrance to Kaumana Lava Tube is in a picnic ground next to Highway 20 (Kaumana Drive) about 6.5 km (4 mi) southwest of Hilo. The area is passed on the way to the Kona Coast via the Saddle Road and is identified by a Hawaii Visitors Bureau sign. Sheltered picnic tables, rest rooms, and drinking water are provided at the facility.

Although it is not the largest lava tube in the islands, Kaumana Lava Tube is an interesting geological formation, displaying many of the features typical of lava tube interiors. It is accessible, relatively easy to walk through, and is in an excellent state of preservation. The tube developed in a historic lava flow (1881, from Mauna Loa), and many aspects of lava tube activity were observed at the time (Baldwin, 1953).

Lava tubes have long been of interest to observers of active flows and many reports contain descriptions of tube formation and activity (e.g., Wentworth and Macdonald, 1953). Interest in lava tubes increased considerably in the last decade through the space program when the possibility of lava tubes and channels on the Moon and Mars arose. As a result, there are several recent papers dealing with lava tube formation (Greeley, 1971b, 1972b; Swanson and Peterson, 1974; Cruikshank and Wood, 1972) and with lava tube morphology (Greeley, 1971a; Greeley and Hyde, 1972; Hatheway and Herring, 1970; and others) to which the reader is referred.

Various geophysical and electromagnetic methods have been used in attempts to find uncollapsed cooled lava tubes. Most of these efforts were unsuccessful or only marginally successful. One relatively successful method was applied to Kaumana Lave Tube by Adams and von Seggern (1969). They used an electromagnetic loop-coupling device that required operators both on the surface and in the lava tube interior. They published their detailed survey as a plan-view map (Fig. 11-3).

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THE 1880-1881 ERUPTION AND 1881 LAVA FLOW

On November 5, 1880 an eruption began on the northwest rift zone of Mauna Loa at about the 3325 m (10,900 ft) elevation, above Puu Ulaula (Fig. 11-1). Initial flows were mostly aa, but later eruptions produced chiefly pahoehoe lavas. The resulting flows constitute a member of the Kau Volcanic Series (Stearns and Macdonald, 1946). The 1881 flow covers 63 km^2 (24 mi^2) and has an estimated volume of $2.3X10^8$ m^3 ($3X10^8$ yd^3). During its early stages of activity, the flow was about 1.5 km wide and moved downslope at a very slow rate (about 800 m per month). In July 1881, as the flow moved through Kaumana Woods (near the entrance to Kaumana Lava Tube), the flow narrowed to a few hundred meters and the forward velocity increased about eightfold (Baldwin, 1953).

E. D. Baldwin observed the 1881 flow from July 12 to July 29 during the period of lava tube activity at Kaumana and elsewhere. He noted (1953) that:

> A pahoehoe lava flow in full motion is a very interesting sight. At the advancing front the lava seems to come out of its tunnel and flow in an open red river of fire as much as several hundred feet long. This then appears to clog up and cool on top, and the lava pushes out in great and small lobes, piling one over the other and eventually forming a new tunnel underneath for the molten lava. The latter will then again break out and go through the same process as before.
>
> At several places there were openings in the top of the flow that exposed the tunnel of red-hot, flowing lava beneath. At one of these, on the steep slope near Kaumana, we threw stones on the flowing lava and timed their passage; we found that the stream of lava was traveling at an average rate of 40 miles an hour in its confining tunnel. This seemed astounding at first, but when one considers that the flow was then more than 1/2 mile wide at its advancing front, the lava would have to be traveling very fast in its narrow channels higher up to supply the broad spread of lava at the front of the flow.
>
> The central supply tunnel was probably 20 to 50 feet wide, with numerous smaller branch tunnels extending from the main tunnel. Often these supply tunnels became blocked; then there would be a sudden outburst of lava,

throwing great blocks of the cooled lava, with the molten lava, into the air.

The 1881 flow posed a serious threat to Hilo (Fig. 11-1) and efforts were made to halt the advancing flow by construction of earth and rock barriers. The barriers, however, remained untested because the flow halted on the outskirts of Hilo (Fig. 11-2), short of the barriers.

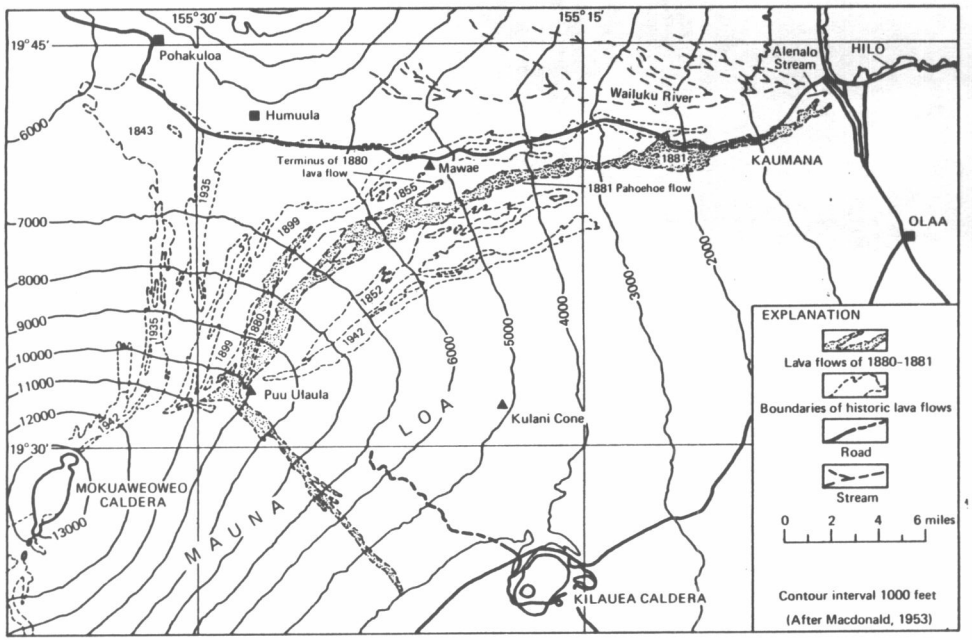

Fig. 11-1. Map of the eastern part of Mauna Loa, showing the 1880-1881 lava flows *(from Macdonald, 1953)*.

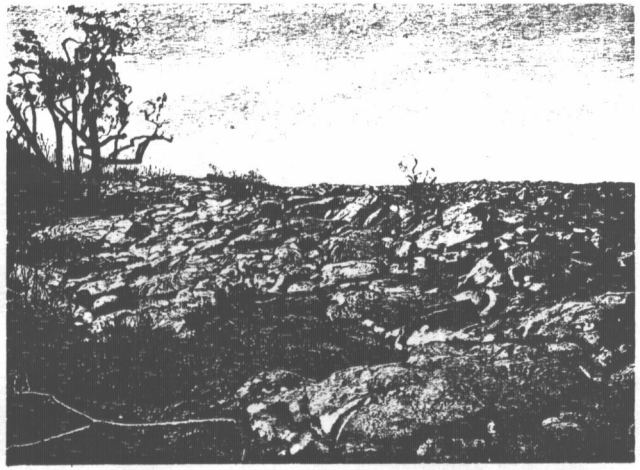

Fig. 11-2. Front of the 1881 pahoehoe flow from Mauna Loa, near the outskirts of Hilo *(from Dutton, 1884)*.

FIELD GUIDE TO THE LAVA LUBE

The lava tube extends both upflow and downflow from the entrance at the picnic ground. This field guide applies only to a short (about 1000 m) section of the lava tube *downflow* (northeast) from the entrance. Figure 11-3 is a plan-view diagram of the tube described here, modified from Adams and von Seggern (1969) and supplemented by Carroll (1954).

Before entering Kaumana Lava Tube, please review these standard caving practices:

1. Do not enter the cave alone.
2. Carry at least three independent light sources (flashlight, candle with matches, carbide lamp, etc.). A camp lantern* is ideal as the primary light.
3. Tell someone when you expect to return and/or leave a note on your vehicle.
4. Wear boots or sturdy shoes.

Although not necessary, a hard hat or bump cap is recommended, as is a lightweight jacket. Photographs can be taken with the aid of flashbulbs, but keep in mind that the dark basalt "absorbs" more light than most surfaces and larger lens apertures than nominal are recommended.

*Can be rented from Holo Holo Campers, Hilo, near airport.

Unlike many limestone caverns, lava tubes are relatively simple. They usually lack multiple, complex passages and getting lost is unlikely (leave the ball of string at home!). However, loose rocks make footing hazardous and holes in the floor of the tube occasionally are encountered that drop through to lower level lava tubes (see Station 3).

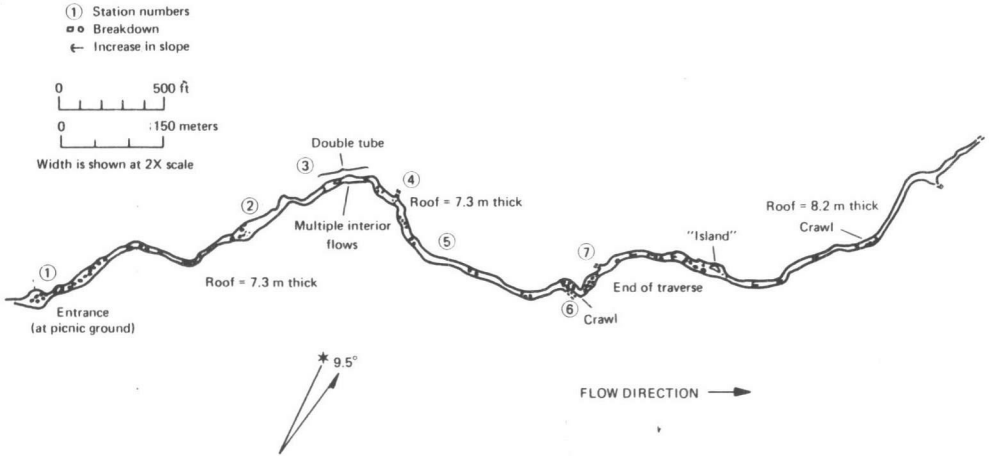

Fig. 11-3. Plan-view of part of the Kaumana Lava Tube, Kaumana, Hawaii *(after Adams and von Seggern, 1969).*

STATION 1

Entrance. The upper part of the flow, constituting the lava tube roof, is poorly developed "layered lava" (Ollier and Brown, 1965), probably formed both from horizontal partings formed during cooling and from accretion of pahoehoe toes. Roof breakdown extends only a short distance into the tube, where it gives way to the original floor of pahoehoe. At the bottom of the stone stairs near the floor and to the right (directions are given facing downtube), note the lava tube *lining*, formed during the drainage of lava from the tube. The lining was probably originally a glassy glaze, but it has weathered in most places to a smooth nonglassy pahoehoe surface. In the latter stages of lava-tube formation, molten lava drained from between the layered lava and dripped onto the lining, observed here and throughout the lava tube.

Notice the large lava block a few meters from the stairs. It is "welded" to the floor and may have been rafted down the tube on the floor-flow.

Fig. 11-4. View near Station 3 of the pahoehoe shelves which merge and divide the tube into an upper level and a lower level. *(Photograph by S. Caceres, Hilo.)*

A short distance inside the tube is a tube-in-tube structure, in which a small lava tube developed in the final flow that drained from the primary tube. Tube-in-tubes, flow fronts, multiple tube linings, and channels along the floor all provide evidence of multiple flows within the tube and are seen throughout the part of Kaumana Lava Tube described here.

STATION 2

The pahoehoe tube lining gradually forms a shelf that extends laterally from the tube walls. At this point, notice that the shelf remains nearly horizontal while the floor of the tube (covered with a transitional pahoehoe-aa flow) continues to drop in elevation.

STATION 3

At this station, the shelves merge to form a continuous platform, resulting in a double tube with an upper and lower level. Multiple tubes can form in several ways (Greeley, 1972b); this section of Kaumana Lava Tube may represent erosion into older lavas, or previously cooled lavas of the 1881 flow.

Take the upper level lava tube and watch for holes in the floor that open into the lower level. About 30 m from the division into two levels, note the stratigraphy of the flows near the wall-floor contact. At least three distinct flows can be discerned; the youngest is reddish orange, the intermediate flow is reddish brown, and the oldest is dark gray. Continue "duck-walking" a few meters downtube, then look back uptube. Three distinct flow fronts, each about 10-20 cm high can be seen.

About 50 m from the division into two levels, the upper and lower levels join to form a single, keyhole-shaped lava tube. Where the upper floor ends, note the same three flows (reddish orange, reddish brown, and dark gray) seen earlier. At this point, it appears that they welled out of the lower level and spilled onto the floor of the upper level a short distance.

STATION 4

A small distributary tube extends to the left (north) about 8 m from the main tube. Many such tubes were described by Baldwin (1953) during observations of the 1880-81 flow.

STATION 5

The lava tube is about 8 m wide, then is abruptly constricted by two massive, rounded swellings that extend into the tube from the walls. Lava tube linings extend up about 2 m on the walls and the protrusions. Driblets of lava originating from near the ceiling accumulated on the lining and the protrusions.

Farther down the tube, levees and gutters occur in the floor flow. In some sections, fallen blocks from the ceiling are incorporated into the floor flow, indicating that they fell while molten lava was still present.

STATION 6

This station marks the beginning of massive breakdown from the ceiling. A small lava tube extends to the right. Take the left-hand (north) side of the tube, which leads to a short "crawl" that is fairly easily negotiated.

From here to Station 7, note many places in which molten lava oozed from the layered lava of the walls and dribbled onto the lower parts of the walls and floor.

STATION 7

A small tube extends to the left. Note the stratigraphy of the multiple flows. The lower part of the secondary tube is truncated by the last flows of the primary tube. However, an older flow appears to have been active in both tubes, indicated by a flowline that is continuous in both tubes.

END OF TRAVERSE

Although the lava tube continues downslope for several hundred additional meters, most of the features are similar to those seen to this point (Figs. 11-5 and 11-6).

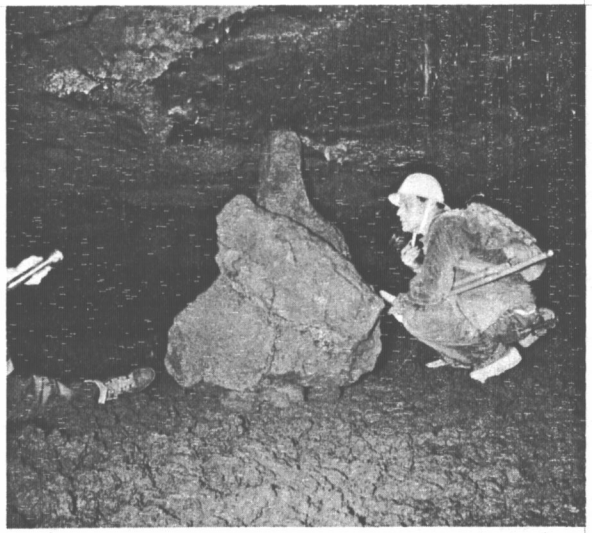

Fig. 11-5. Meter-size block that was rafted downtube on a floor flow. At this point, the block wedged between the floor and the ceiling. *(Photograph by S. Caceres, Hilo.)*

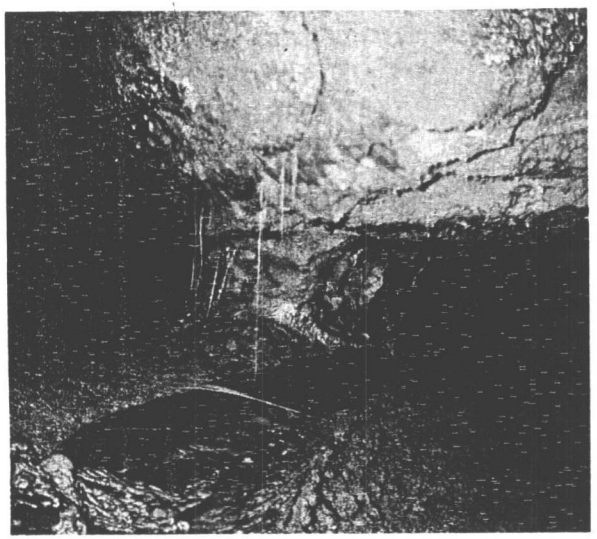

Fig. 11-6. "Island," about 1.5 m wide, in the tube. Note the younger flow that passed to the right of the island, indicated by the glazed lava gutter of the flow, and the later "dribble" of lava on the gutter (lower left). *(Photograph by S. Carceres, Hilo.)*

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N94-34787

12. MAUNA KEA

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Driving time from downtown Hilo to starting point at intersection of State Route 20 and the Hale Pohaka Road: 45 minutes.
Field trip time required: approximately 5 hours (not including round-trip drive from Hilo).

NOTE: 4-wheel drive vehicle is required from Hale Pohaka to the summit.

Mauna Kea (Fig. 12-1), the highest of Hawaii's five volcanoes, is the only high landmass in the central Pacific Ocean basin to bear unmistakable signs of Pleistocene glaciation. The stratigraphic record indicates that a summit ice cap formed and disappeared at least four times in the last 250,000 years, and that volcanic eruptions characterized not only the interglacial intervals, but also two of the glacial periods as well.

Exposed rock units on the upper slopes of Mauna Kea have been divided into two major groups based on gross lithologic character. The Hamakua Group comprises the bulk of the subaerial shield of the volcano and consists largely of thin-bedded pahoehoe flows of olivine basalt. The overlying Laupahoehoe Group consists of a thin cap of alkalic lavas and pyroclastic layers confined largely to the upper slopes of the mountain. Interstratified with the volcanic units are sedimentary formations that provide evidence of four episodes of ice-cap glaciation. These are designated, from oldest to youngest, Pohakuloa, Waihu, early Makanaka, and late Makanaka. The drift sheets have been used to subdivide the volcanic rocks on the upper slopes of the mountain into a number of formations (Fig. 12-2).

Figure 12-3 is a strip map along the road to the summit of Mauna Kea, showing the geology, their stratigraphic relations, and stops for the field trip.

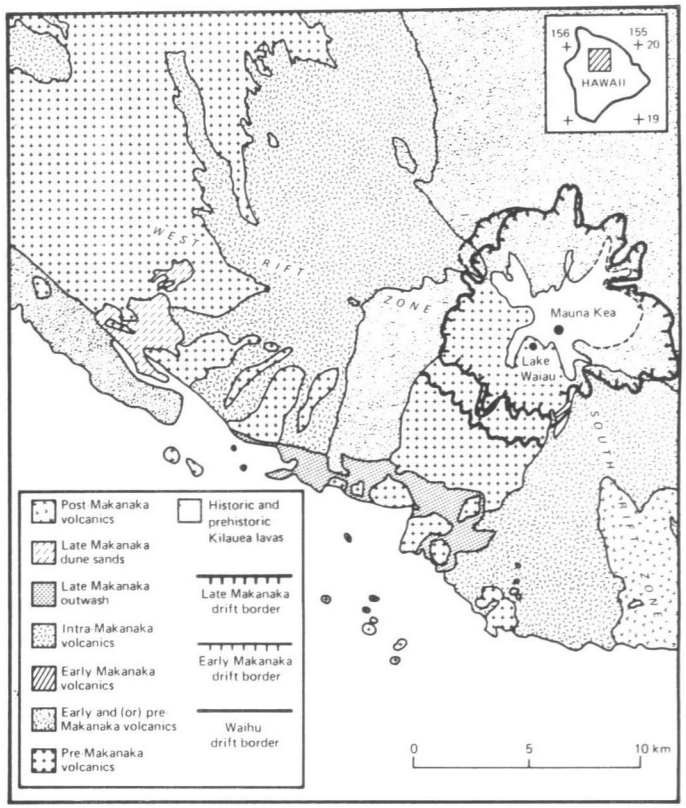
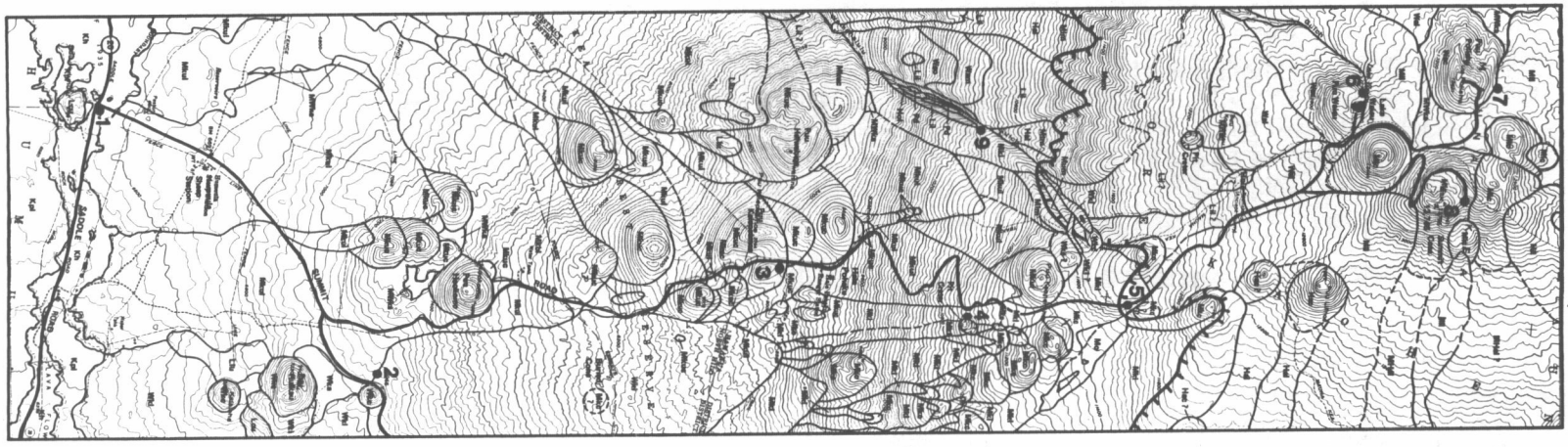


Fig. 12-1. Generalized geologic map of the upper slopes of Mauna Kea *(from Porter, in press)*.

LAUPAHOEHOE GROUP	Waikahalulu Formation (V)	
	Makanaka Formation	Upper Member (G)
		Kemole Member (V)
		Lower Member (G,V)
	Hanaipoe Formation (V)	
	Waihu Formation (G,V)	
	Liloe Formation	
HAMAKUA GROUP	Pohakuloa Formation (G)	
	Hopukani Formation (V)	

Fig. 12-2. Stratigraphic section on upper slopes of Mauna Kea (V = volcanic units; G = glacial unit).



PLEISTOCENE								HOLOCENE			
Hamakua Group		Laupahoehoe Group									
Hopukani Formation	Pohakuloa Formation	Liloe Formation	Waihu Formation	Hanaipoe Formation	Makanaka Formation			Waikahalulu Formation	Kau Formation (Mauna Loa)		
					Lower Member	Kamole Member	Upper Member		Prehistoric Member	Historic Member	
Pre-Pohakuloa lava flows [Hvl]		Liu Laupahoehoe lava flows (undifferentiated)									Lava Flows
		Pre-Waihu, post-Pohakuloa lava flows [Ll]	Intra-Waihu lava flows [Wvl]	MHal Pre-late Makanaka, post-Waihu lava flows	Early Makanaka lava flows [Ml]		Kamole or post-Kamole lava flows [Mkvl]	Post-Makanaka lava flows [Hvl]	Prehistoric lava flows [Pvl]	1926 flow [Ovl]	
				Pre-Makanaka, post-Waihu lava flows [Hvl]		Late Makanaka lava flows [Mvl]					
		Lou Laupahoehoe cinder cones (undifferentiated)									Tephra Cones
		Pre-Makanaka, post-Waihu cinder cones [Ll]	Intra-Waihu tephra cones [Wtc]	MHac Pre-late Makanaka, post-Waihu cinder cones	Early Makanaka intrigated tephra cones [Mtc]		Kamole or post-Kamole cinder cones [Mkcc]	Post-Makanaka cinder cones [Hcc]			
				Pre-Makanaka, post-Waihu lava flows [Hvl]		Late Makanaka cinder cones [Mcc]					
	Pohakuloa drift [Pd]		Waihu erosional unconformity deposits [Wsu]		Early Makanaka erosional unconformity deposits [Msu]		Late Makanaka erosional unconformity deposits [Msu]				Glacial Drift
			Waihu moraines [Wm]		Makanaka moraines [Mm]						
					Makanaka and post-Makanaka alluvium [MHAa]			Post-Makanaka alluvium [Ha]			Alluvium

Fig. 12-3. Geologic map for the area along the Hale Pohaka Road to the summit of Mauna Kea.

STOP 1

The first station is at junction of Saddle Road (State Route 20) and the road to Mauna Kea summit (6578 ft). The Saddle Road is built across 1935 Mauna Loa pahoehoe lava, which flowed north into the Mauna Loa-Mauna Kea saddle, then east in the direction of Hilo. The flow surrounds Puu Huluhulu, a Pleistocene cinder cone of Mauna Kea. To the north, cinder cones and lava flows (Figs. 12-4 and 12-5) of the south rift zone of Mauna Kea fill the view. A light-colored band of rock seen near the top of the mountain is the moraine complex built during the last two ice-cap glaciations (early and late Makanaka).

The lower south slopes of the mountain are underlain by Pleistocene lava flows capped by numerous sheets of tephra erupted from cinder cones of late Pleistocene and Holocene age. In road cuts and shallow gullies near Humuula, Holocene tephra can be seen resting on a buried soil (Humuula soil) that is developed on reworked older tephra and on lava. The Holocene tephra thickens and coarsens toward the northeast where a complex of cinder cones (Huikau, Loaloa) marks the source vents.

STOP 2

Here we see a type section of Humuula soil in gully at 7070 ft, 1.6 km (1 mi) north of Huikau. A typical stratigraphic section of the Holocene tephra succession and the Humuula Soil (Tables 12-1 and 12-2) are exposed in the walls of this gully. On the southwest side of the gully, the buried soil is developed on reworked late Pleistocene tephra and overlain by two tephra units, a thin layer from Puu Kole and a thick complex unit derived from vents east and south of this locality. Charcoal from the buried soil has an average age of about 4500 ^{14} C yr. Profile characteristics of the buried soil are stronger than those of the surface soil, suggesting it probably formed during an interval somewhat longer than 4500 yr. The eastern wall of the gully is largely formed by the Hale Pohaku lava flow (Figs. 12-6 and 12-7) which overlies the Humuula Soil and the Puu Kole tephra, but underlies the Loaloa-Huikau tephra complex. This flow originated at 9000 ft just east of Hale Pohaku and underlies the flow complex erupted from the Loaloa, Huikau, and related vents.

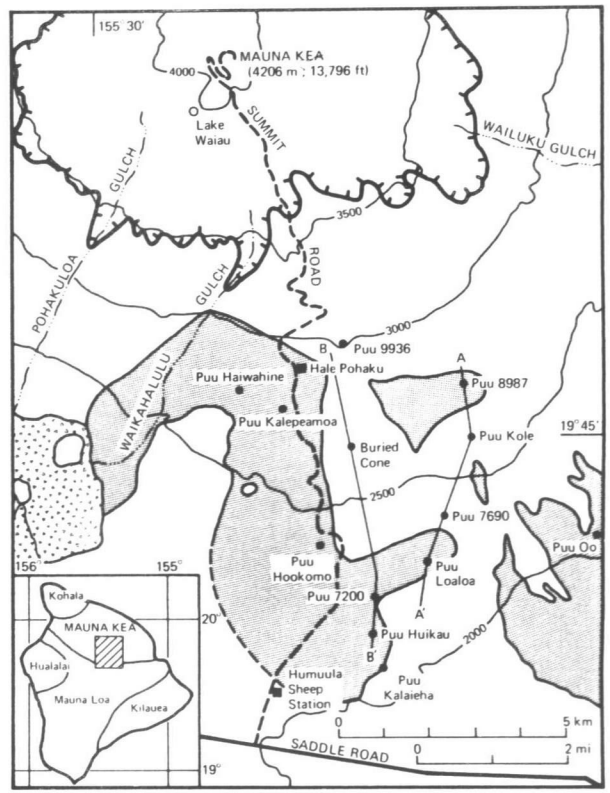


Fig. 12-4. South rift zone of Mauna Kea showing areas (shaded) where surface tephra layers reach or exceed a thickness of 1 m. Heavy ticked line indicates limit of youngest glacial drift (Makanaka). Outwash fans at base of mountain are indicated by stippled pattern. Numbered cinder cones (puus) are in feet; contours are in meters *(from Porter, 1973)*.

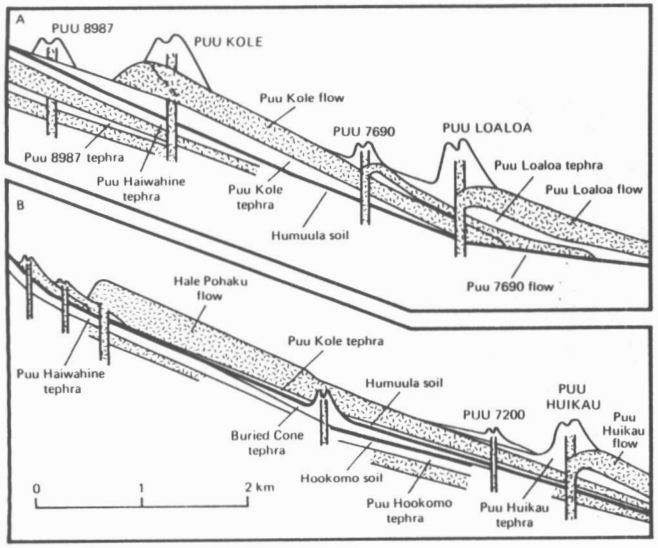


Fig. 12-5. Stratigraphic relations of tephra units, lava flows (patterned), and buried soils (black) along lower south rift zone. Vertical dimension not to scale. Transect A lies 1.5 km east of transect B *(from Porter, 1973)*.

TABLE 12-1. PRINCIPAL TEPHRA LAYERS AND BURIED SOILS OF THE LOWER SOUTH RIFT ZONE AT MAUNA KEA

Puu Loaloa – Puu Huikau tephra complex
Puu Kole tephra
Humuula scil
Buried Cone tephra
Puu Haiwahine tephra
Puu 8987 tephra
Hookomo soil
Puu Kookomo tephra

TABLE 12-2. PETROGRAPHIC CHARACTERISTICS OF TEPHRA LAYERS ON THE SOUTH RIFT ZONE OF MAUNA KEA

Tephra layer	Refractive index	Mean composition of olivine crystals	Mean composition of plagioclase crystals	Plagioclase/olivine ratio (range)
Puu Loaloa–Puu Huikau complex	1.557 ± 0.001	..	..	..
Puu Kole	1.563 ± 0.006	..	..	..
Buried Cone	1.571 ± 0.006	Fo_{76}	$An_{50\pm13}$	0.05 to 0.20
Puu Haiwahine	1.572 ± 0.003	Fo_{71}	Insufficient data	0 to 0.05
Puu 8987	1.578 ± 0.003	Fo_{75}	$An_{39\pm11}$	0.25 to 0.50

Data from W. E. Scott (1971, written commun.).

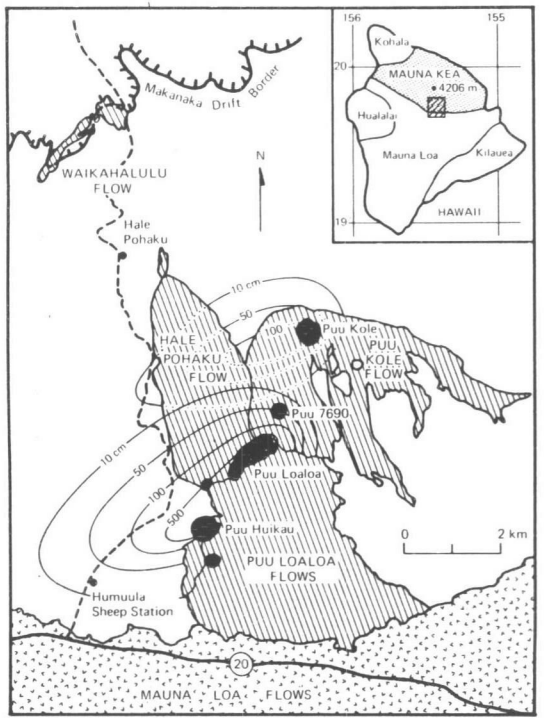


Fig. 12-6. Distribution of Holocene cinder cones (black) and lava flows (shaded) on the south slope of Mauna Kea. Isopachs drawn on Puu Kole and Puu Loaloa tephra layers are given in centimeters. The location of State Highway 20 is indicated in the area of the Mauna Loa flows *(from Porter, 1971)*.

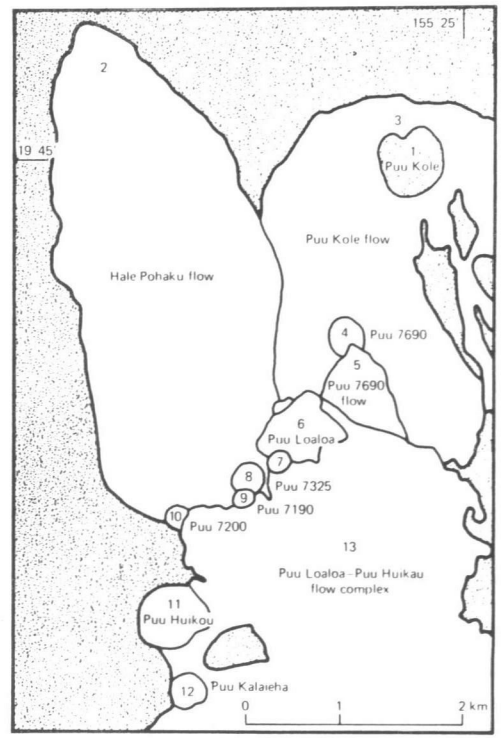


Fig. 12-7. Order of eruptions of Holocene volcanic units on lower south rift zone. Pre-Holocene volcanic rocks indicated by shaded pattern *(from Porter, 1973)*.

STOP 3

This station is at the rim of Puu Kalepeamoa (Fig. 12-8) at 9100 ft, one of a series of cinder cones erupted along the south rift zone during the late Pleistocene. Successively younger cones and flows overlap older units progressively downslope. Puu Kalepeamoa is distinctive among the cones near the road in having a large number of cored bombs. Angular mafic blocks form the cores of many bombs, with dunite and gabbro being among the most common inclusions seen. The series of cones and flows west of Hale Pohaku appears to lie stratigraphically below drift of the last glaciation (late Makanaka) but above that of the next older glaciation (early Makanaka).

STOP 4

A short walk east of Summit Road (10,900 ft) is the edge of one of the two known pit craters on Mauna Kea. This one is about 30 m (100 ft) deep and is nearly unmodified except for mass wasting along its walls. Another pit crater west of the road at 12,200 ft was overridden by glacier ice and has been partly filled and eroded. Although the two oldest ice caps of Mauna Kea (Waihu and Pohakuloa) extended below 10,900 ft, drifts of these ages are not seen in the walls of the pit crater; presumably they lie at greater depth. All exposed flows postdate the Waihu glaciation and probably the early Makanaka glaciation as well.

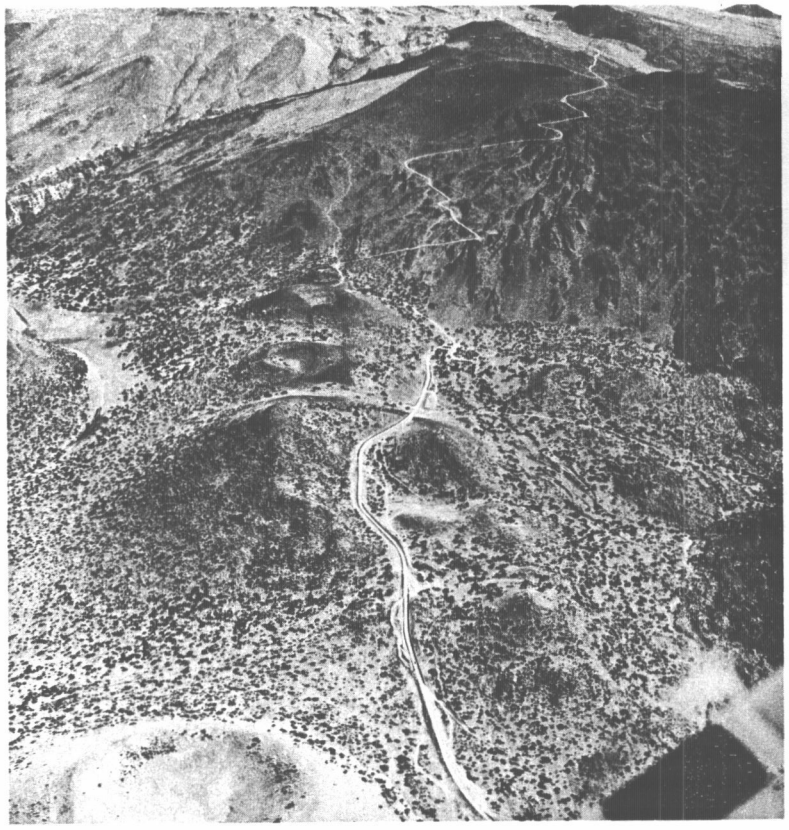


Fig. 12-8. Oblique aerial view of the south flank of Mauna Kea. Hale Pohaka is the cluster of buildings in the center of the picture. The road cuts across Puu Kalepeamoa. *(Photograph by Ronald Greeley, University of Santa Clara, June 1974).*

STOP 5

The limit of late Makanaka drift on Summit Road at 11,600 ft is marked by deposits of medium-gray rounded hawaiite boulders. Below this level, lava flows are unmodified by glacial activity, but upslope they have been smoothed and polished by the late Makanaka glacier. A broad apron of outwash sand and gravel extends downslope from the drift border. Drifts of early Makanaka and of pre-Makanaka age have not been identified in this area, so lava flows beneath the surficial glacial drift are presumed to be intra-Makanaka flows (Kemole Member). Lava from the big cinder cone west of this stop overlies early Makanaka moraine along Waikahalulu Gulch and, in turn, is overlain by late Makanaka drift.

STOP 6

Lake Waiau (13,020 ft) is the only lake on the upper slopes of Mauna Kea and is the highest lake in Hawaii. It lies in the crater of Puu Waiau, one of the two large pyroclastic cones erupted during the Waihu glaciation. The steep lava rampart along the north side of the lake basin is an ice-contact flow margin formed during the early Makanaka glaciation when lava and pyroclastics erupted from a series of vents near the summit along the perimeter of an inferred former summit caldera. The surface of the early Makanaka flow is abraded and striated, a result of late Makanaka glaciation. The presence of the lake has been ascribed to (1) ground ice and (2) impermeable drift. A more satisfactory explanation for the lake, however, lies in the composition of the cone, which is largely of relatively impermeable hyaloclastite. Coring has shown that some 11 m of sediment underlie the water column and that the upper 4 m were deposited during the last 9000 yr. The lower sediments apparently are inorganic and not dated, but they very likely were deposited during a brief period as the last glacier melted from the summit, probably about 12,000 to 13,000 yr ago.

By following the gully beyond the lake outlet downslope for about 60 m, one can see the sediments comprising the cone. These consist of even-bedded bomb-bearing hyaloclastite capped by bomb-rich cinders. The hyaloclastite is inferred to have been deposited in a lake melted in a summit ice cap by subglacial eruptions during Waihu time. The thickness of hyaloclastite, as well as the ice-contact slopes of lava flows erupted during this interval, indicate that ice was between 100 m (300 ft) and 120 m (400 ft) thick. The capping of cinders is believed to have formed when the accumulating pyroclastics had filled the meltwater lake and subaerial, rather than subaqueous, pyroclastic activity took place.

STOP 7

Puu Poliahu (13,300 ft) is another Waihu pyroclastic cone, which consists largely of subaqueously deposited hyaloclastite. Unlike Puu Waiau it does not contain a lake because its summit crater has been breached by erosion. Walking along the north side of the cone, one can see the well-developed ice-contact margin of the McCrae Cone flow, which was erupted during the early Makanaka glaciation. The flow margin is steep and abrupt; it is characterized by large bulbous pillow-like structures having radial jointing and glassy, locally palagonitized surfaces. Spiracles as much as 2 m high rise above the base of the flow. This flow, like others of the same age inside the glacial border, has embayed fronts and steep margins that rise as much as 30 m (100 ft) above adjacent terrain.

STOP 8

Flows associated with the cluster of cinder cones near the summit have ice-contact margins and are inferred to have been erupted while ice covered the slopes of the summit of Mauna Kea (13,796 ft). The cones appear to be typical cinder cones. However, roadcut exposures in the flanks of Summit Cone display considerable hydrothermal alteration of the volcanic sediments, a feature not seen in any cones lying outside the glacial limit. A seismic discontinuity was detected about 15 m above the base of the cone and is thought to mark the transition from subaqueously deposited pyroclastics to normal subaerially deposited cinders. If this interpretation is correct, other early Makanaka cones at the summit may also have a core of hyaloclastite deposited in lakes melted in the summit ice cap.

STOP 9

A traverse west from the Summit Road at ~10,300 ft level for about 1.6 km brings one to the upper end of the deep gorge of Waikahalulu Gulch. Here the entire stratigraphic section is exposed in the steep cliffs. The lowest lavas belong to the Hopukani Formation, the oldest rocks exposed on this side of the mountain. They are overlain by the Pohakuloa Formation, the oldest exposed glacial drift. This unit contains only olivine basalt and related rocks of the main shield; hawaiite and related alkalic lithologies are absent. Lavas above the Pohakuloa belong to the Liloe Formation and include alkalic rock types. In upper Waikahalulu Gulch Liloe tephra and dikes are exposed near the head of the gorge. Glacial drift of the Waihu Formation lies at the surface along the west rim of the gulch, but it is buried beneath younger lavas on the east rim. These lavas are part of the Kemole Member of the Makanaka Formation and overlie the early Makanaka terminal moraine upslope. They are overlain, in turn, by drift of the Upper Member of the Makanaka Formation, deposited during the last ice advance. A thousand feet higher up the gulch, the late Makanaka moraine is overlain by a cinder cone and associated lava belonging to the Waikahalulu Formation. Probably these represent the latest episode of volcanism on the mountain, tentatively dated at 3600 ^{14}C yr ago.

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N74-34788

13. EAST PUNA

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Total time roundtrip from Hilo: 6-1/2 hours
Total road distance: approximately 130 km (80 mi)

This field trip mostly involves volcanic features that can be seen from roads in the east Puna District. Most of the features are associated with the eruptions of 1750(?), 1790(?), 1840, 1955, 1960, and the recent flows from Mauna Ulu on the Keauhou Lava Plains during the years 1969-1973. Particular emphasis is given to the 1955 and 1960 volcanic activity that occurred near the village of Kapoho.

STRUCTURAL AND HISTORIC SETTING
(from Macdonald and Eaton, 1964)

Kilauea is a typical shield volcano, built against the side of the larger shield of Mauna Loa. Within its summit caldera is the collapse crater, Halemaumau, which for a century previous to 1924 was the site of nearly continuous lava-lake activity. Extending both southwestward and eastward from the caldera are rift zones, along which most of the flank eruptions of the volcano have taken place (Stearns and Macdonald, 1946, p. 129, pl. 1). The east rift zone trends southeastward from the caldera for 7.3 km, then makes an abrupt bend and continues N. 65° E. to and beyond Cape Kumukahi, the easternmost point of the island of Hawaii (Fig. 13-1). It is marked by numerous open fissures, cinder and spatter cones, and pit craters (Figs. 13-2 and 13-3). More than 70 vents, from which lava poured out onto the surface, can be recognized along the east rift zone, and these represent only the ones that have not yet been buried by later flows. There must be many hundreds more beneath the surface. Extrusion of fluid flows of basaltic lava from vents along the rift zone has resulted in the building of a broad constructional arch, with its crest at the rift zone.

The south side of the rift-zone arch has been steepened by faulting. Although the scarps have been almost wholly buried by later lava flows, their topographic expression remains clear (Stearns and Macdonald, 1946, p. 40, 129-130; Wentworth and Macdonald, 1953, p. 21). One such buried fault scarp lies along the south side of the rift-zone ridge 10 to 20 km southwest of Cape Kumukahi (Stearns and Macdonald, 1946, pl. 1) and forms unusually steep slopes in the Kamaili and upper Kaueleau areas.

Flank eruptions of Kilauea have been much less frequent in the short span of historic time in Hawaii than have those of Mauna Loa. Small brief eruptions occurred on the east rift zone just east of the bend in 1922 and 1923 (Jaggar, 1922; Finch, 1923). Previous to that, the last had been in 1840, when eruption on the upper part of the east rift zone was followed by a voluminous outpouring of picrite-basalt rich in phenocrysts of olivine from the lower part of the rift zone 13 km southwest of Cape Kumukahi (Macdonald, 1944, p. 178-181). The head of the principal lava flow of 1840 is south of Pahoa. About 1790 another lava flow had occurred in the same general area, and about 1750 another had issued somewhere in the vicinity of Heiheiahulu cone, and flowed into the ocean northeast of Kalapana, 22.7 km southwest of Cape Kumukahi (Macdonald, 1941).

Still other, earlier eruptions are mentioned in the unwritten legends and traditions of the Hawaiian people, but their dates are very uncertain. Unquestionably, a large proportion of the area of east Puna must have been inundated with lava during the last thousand years.

SUMMARY OF THE 1955 ERUPTION
(from Macdonald and Eaton, 1964)

Prior to the 1955 eruption, the last lava activity on the east rift zone had been in the vicinity of Makaopuhi Crater, in 1923. Not since 1840 had there been activity in eastern Puna. In 1924, however, a very large number of earthquakes along the east rift zone accompanied the draining of lava from Halemaumau Crater in the caldera and the formation of fault scarps and grabens in eastern Puna. The eastern outbreaks in 1955 closely followed the lines of fissuring and faulting in 1924 (Fig. 13-1).

The eruption began on the morning of February 28, near Puu Honuaula, 38.9 km east-northeast of Kilauea caldera. It was preceded for several months by earthquakes, which gradually increased in number to several hundred a day just before the outbreak. Lava activity at the initial vents continued for only 28 hours and on March 1 was replaced by mild phreatic explosions and clouds of steam.

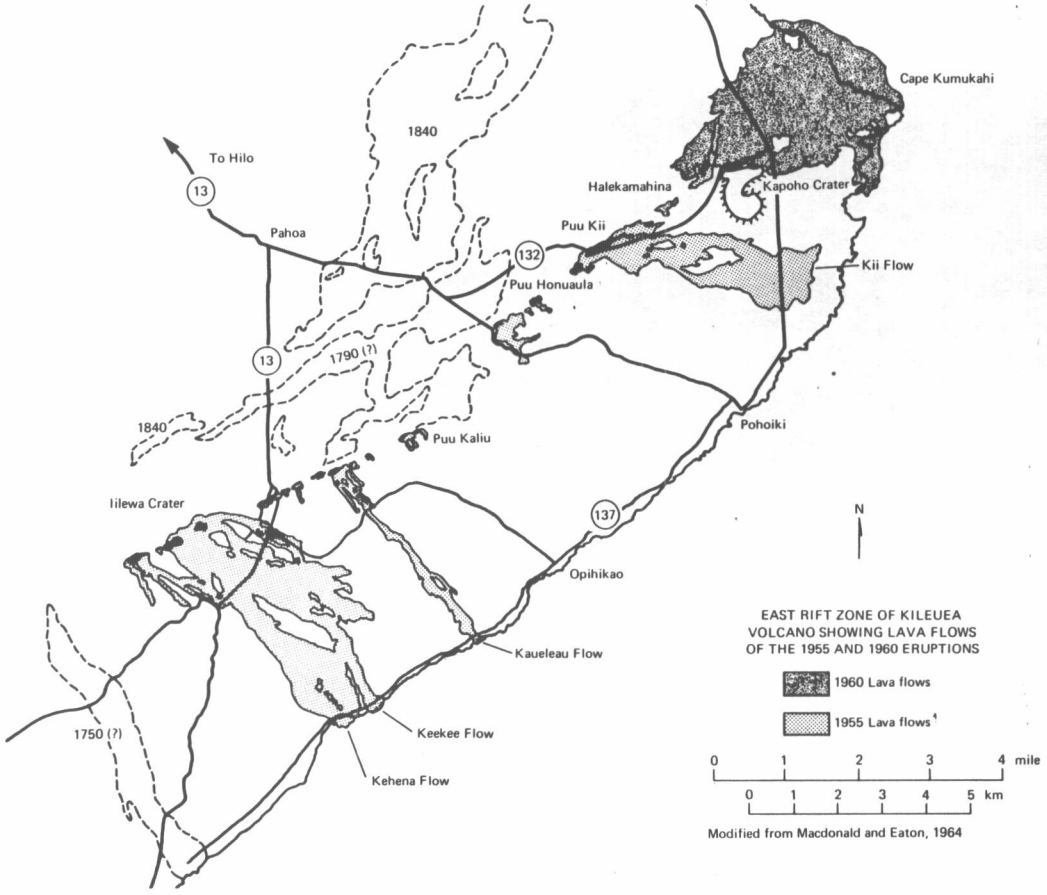


Fig. 13-1. Geological sketch map of the east rift zone of Kilauea Volcano *(after Macdonald and Eaton, 1964; Richter et al., 1970).*

Fig. 13-2. Spatter and cinder cones at the vents of some of the lava flows of 1955, on the east rift zone of Kilauea Volcano *(Macdonald and Abbott, 1970; Hawaii Institute of Geophysics photograph by Agatin T. Abbott).*

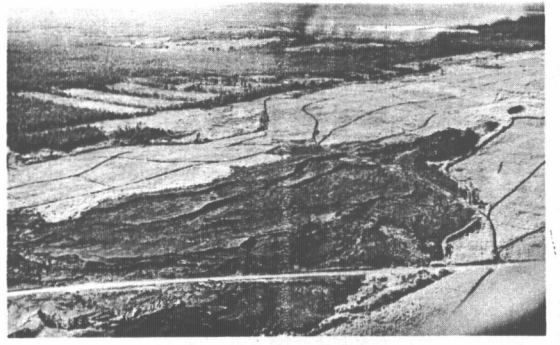


Fig. 13-3. Lava flows and spatter cones on the east rift zone of Kilauea Volcano, east Puna District. *(Hawaii Institute of Geophysics photograph by Agatin T. Abbott.)*

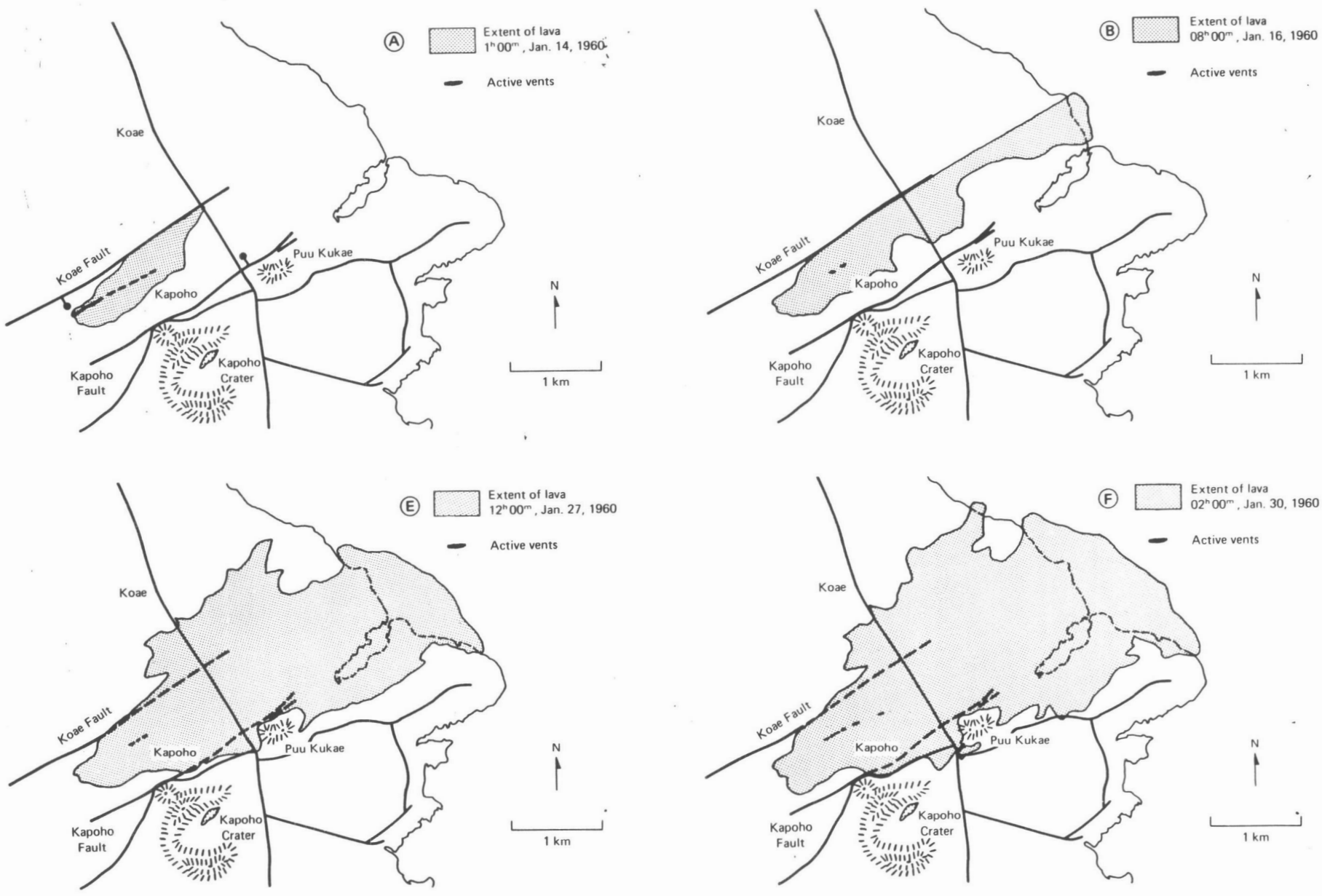
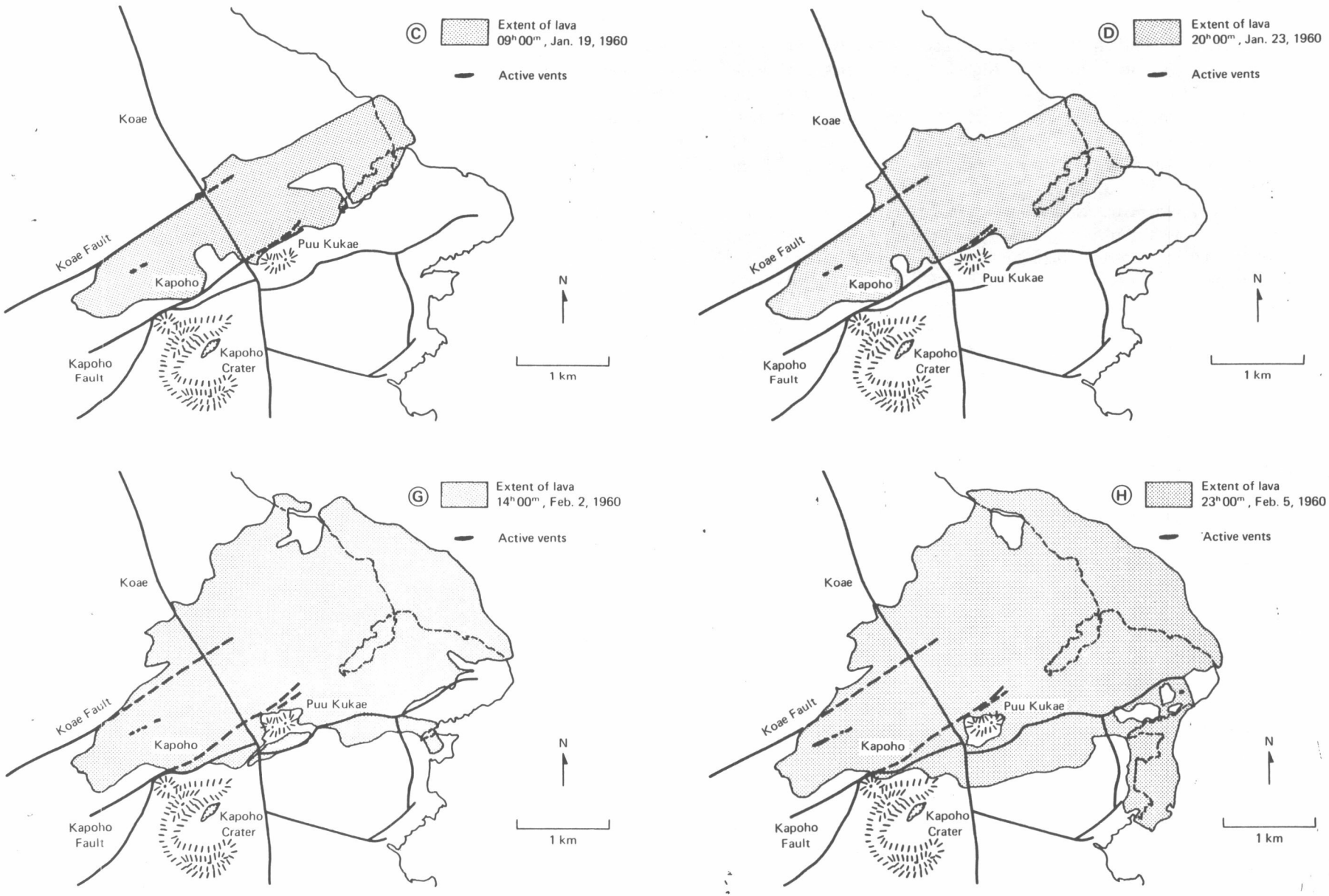


Fig. 13-4. Sequential diagram showing the advance of lava flows during the 1960 activity in the vicinity of Kapoho, east Puna District ***(after Richter, 1970)***.


Ⓒ
Extent of lava
09h00m, Jan. 19, 1960
Active vents
Koae
Koae Fault
Puu Kukae
Kapoho
Kapoho Fault
Kapoho Crater
N
1 km
Ⓓ
Extent of lava
20h00m, Jan. 23, 1960
Active vents
Koae
Koae Fault
Kapoho
Puu Kukae
Kapoho Fault
Kapoho Crater
N
1 km
Ⓖ
Extent of lava
14h00m, Feb. 2, 1960
Active vents
Koae
Koae Fault
Puu Kukae
Kapoho
Kapoho Fault
Kapoho Crater
N
1 km
Ⓗ
Extent of lava
23h00m, Feb. 5, 1960
Active vents
Koae
Koae Fault
Puu Kukae
Kapoho
Kapoho Fault
Kapoho Crater
N
1 km

On March 2 a new series of earthquakes accompanied the formation of fault scarps and opening of fissures 3.2 km farther northeast, and at 14^h15^m lava broke out on these fissures. Through the next 2 days the eruptive fissures gradually extended another 3.2 km northeastward, to the outskirts of Kapoho village. Lava fountains at the main vents reached a height of at least 244 m and flows from them covered approximately 4.5 km^2. Activity in that area stopped on March 6.

On March 6 a new series of earthquakes commenced, originating in the area 3 to 20 km southwest of the initial outbreak, and a new outbreak in that area was predicted. On March 12 lava broke out in that region, and between then and March 27 a series of new vents developed along the rift zone for 6.5 km to the southwest. Three lava flows from these vents entered the ocean.

Activity ceased on April 7 but resumed weakly on April 24 and gradually increased until a strong resurgence occurred on May 16. New flows covered much of the area covered by the heads of earlier flows, and some new area, destroying one village. The eruption ended abruptly on May 26.

The volume of erupted material was approximately 108×10^6 m^3. The flows covered an area of about 16 km^2 of which 4.5 km^2 was under cultivation. Approximately 10.2 km of public road and many kilometers of canefield road were buried, and 21 houses were destroyed. There were no human casualties.

The erupted lavas were basalt, becoming slightly more mafic as the eruption progressed. The temperature of lava as it was erupted was approximately 1,100° C.

The eruption was preceded by swelling of the rift zone, producing a rise of the ground surface of about 30 cm. The several outbreaks of lava were accompanied by sinking of grabens along the crest of the rift zone. The sinking commonly exceeded 30 cm and locally exceeded 1.5 cm. Stretching of the surface across the areas of eruption resulted in the shifting of known points as much as 1.5 m in a direction normal to the rift zone.

A gradual tumescence of the volcano commenced in January 1953 and continued until the 1955 outbreak, with virtually no interruption by the brief eruption in the caldera in 1954. During the 1955 eruption there was a sinking of as much as 42 cm in the caldera region. The calculated volume of sinking in the summit region of the volcano had the same order of magnitude as the volume of lava extruded in east Puna. The lava was not, however, simply drained from under the caldera, because the composition of the erupted lavas was appreciably different from that of the lava erupted in the caldera in 1954.

SUMMARY OF THE 1960 ERUPTION
(from Richter et al., 1970)

In the evening of November 14, 1959, a summit eruption occurred in Kilauea Iki, a collapse crater adjacent to the main summit caldera of Kilauea. The eruption consisted of 17 separate eruptive phases, which ranged in duration from 1 week to 1-3/4 hours. At the cessation of activity on December 20, 1959, Kilauea Iki Crater held 38×10^6 m^3 of lava in a lake 102 m deep.

After the cessation of eruptive activity in Kilauea Iki on December 20, 1959, tilt measurements continued to show swelling of the summit area; this swelling strongly suggested that magma was still moving into the volcano and that the eruption was not over. Late in December, earthquakes along Kilauea's east rift zone, 40.5 km from Kilauea Iki gave the first indication of magma moving out of the summit area. By mid-January the earthquake activity had migrated downrift to the vicinity of the village of Kapoho, and on January 13, 1960, faults bounding an old graben, which contained part of the village, were reactivated and the graben began to subside.

At 7:30 that evening the flank eruption began along a line of en echelon fissures that extended through the middle of the graben a few hundred meters north of the village (Fig. 13-4). The main fountain area, 3.2 km from the sea coast, soon produced a steady stream of lava that slowly flowed down through the graben and reached the sea on the night of January 15. By the end of the first week of eruption the low graben was virtually filled. Besides continuing to push slowly into the sea, flows began to spread laterally out of the graben. These flows gradually destroyed most of the village of Kapoho (Fig. 13-5), the smaller community of Koae, the United States Coast Guard station at Cape Kumakahi, and a number of beach residences along the coast. Although the extrusion of lava had virtually ceased by February 6, 1960, the main vent continued to emit gas, pumice, cinders, and minor spatter until February 20 when the eruption ended. The flank activity produced approximately 122×10^6 m^3 of lava and covered about 10.2 km^2 including about 2 km^2 of new land beyond the former coastline (Fig. 13-6).

On January 17, 1960, 4 days after the beginning of the flank eruption, tilt measurements revealed that the summit was rapidly deflating, evidently because of a massive withdrawal of magma from the summit area. By the end of January, a swarm of strong shallow earthquakes was occurring under the caldera area, and new cracks and steaming areas had begun to develop on the floor of Halemaumau. Then, on

February 7, a fissure apparently extended up into the still liquid core of the 1952 lava lake in Halemaumau, thus allowed lava to drain away and resulted in a rapid collapse of Halemaumau's floor. On February 9 and March 11 two smaller collapses occurred in the bottom of Halemaumau; the latter ended the summit collapse of the 1959-60 eruption sequence. Total volume of the three collapses in Halemaumau was approximately 22.1×10^6 m^3.

Fig. 13-5. Laimana cone, east Puna District, photographed from the site of Kapoho, a town which it engulfed with lava and tephra during the 1960 eruptions on the east rift zone of Kilauea Volcano. Volcanic bombs thrown from the cone during eruptions produced a field of impact craters on the opposite side of the cone (Hartmann, 1967). *(Photograph by Dale Cruikshank, University of Hawaii, 1967.)*

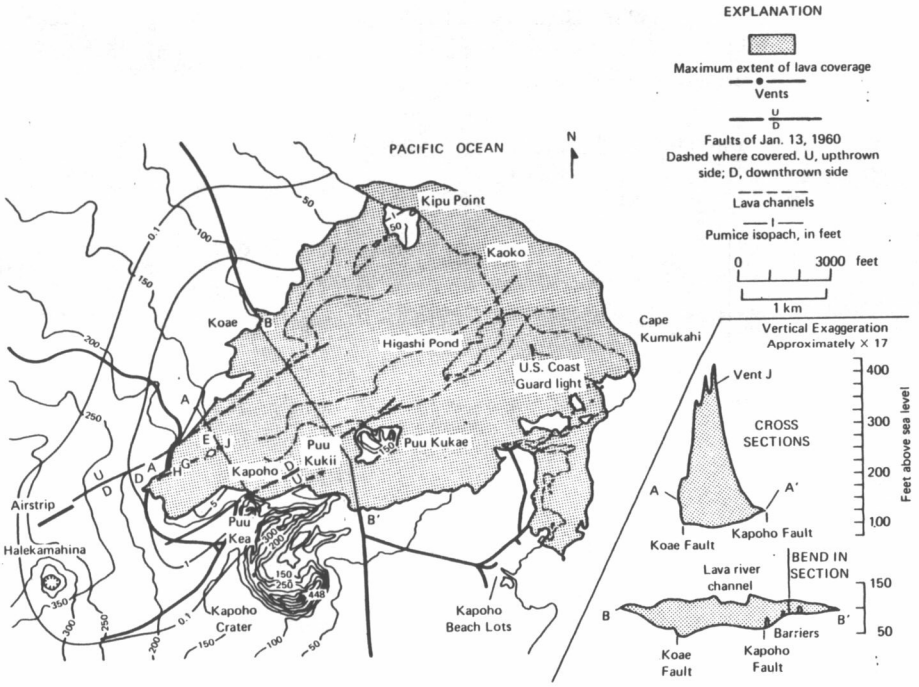


Fig. 13-6. Map and cross sections of the 1960 eruption area, east Puna District, showing maximum extent of lava coverage and isopachs of the pumice blanket *(after Richter et al., 1970)*.

ROAD GUIDE

Mileage from Hilo Airport	
0.0	Hilo Airport. Proceed south on Highway 11.
3.5 - 7.0	Road crosses prehistoric lava flows of Mauna Loa. Road cuts expose cross sections of mostly aa flows of tholeiitic basalt.
7.0	Junction with Highway 13, at Keaau. Turn left on Highway 13. The road continues over Mauna Loa lavas with enough soil cover to support sugar cane.
8.3	Contact with Kilauea lavas, which have less soil and no cane.
8.5 - 12.0	Roadcuts expose cross sections of prehistoric pahoehoe flows of Kilauea.
12.0 - 14.4	The very fresh pahoehoe surface in this area was probably formed about 1400 A.D. by flows from the east rift zone of Kilauea in the vicinity of Kalalua Crater. The road continues across older pahoehoe lava flows.
17.8	Center of Pahoa town.
18.2	Junction with Highway 132. Turn right on Highway 13.
19.6	The vents of the main lava flow of the 1840 eruption are in the forest to the left.
20.3	Intersection with Leilani Ave. Vents of the 1790 lava flow lie on both sides of the road in the forest.
21.0	Crest of the broad rounded ridge built by eruptions on the east rift zone of Kilauea.
21.7	Large parking area on left side of road. Just seaward of the road are spatter cones built at vents of the 1955 eruption.
22.0	Intersection with road to Opihikao.
22.3	Edge of a big aa flow of the 1955 eruption. The cones at the vents from which the flow issued can be seen 0.8 mi inland. Road cuts expose cross sections of the aa flow units.
23.1	On the right is a wooded kipuka (island) in the flow.
23.3	Edge of the 1955 lava flow.
26.3	The road crosses an aa lava flow erupted about 1750. Where this flow entered the ocean, steam explosions ("littoral explosions") threw up a spray of liquid lava drops, which chilled to black glass and were drifted along shore by currents to form the black sand beach at Kaimu.
27.2	Junction with Highway 137, at Kaimu Beach. Turn right on Highway 13.
27.6	Parking area at south end of Kaimu Beach. Because there is no continuous source for the sand, which was formed only in the single episode in 1750, the normal beach cycle is resulting in a steady decrease in the size of the beach. It has been cut back several hundred feet in the last century.
28.1	Harry K. Brown Beach Park. Rest rooms. A heiau (temple) platform lies at the southwest side of the park, near a pool of brackish water fed by basal springs.
28.3	On the left, dunes of black sand blown inland from the beach.
28.5	Kalapana village lies in a shallow graben on the south flank of Kilauea. In 1868 the floor of the graben sank several feet, during the most severe series of earthquakes in Hawaii's history. In the next half mile one of the bounding fault scarps is visible seaward from the road.

30.0 Beginning of new highway. Ahead to the right, the steep escarpment is a series of fault scarps mantled with later lava flows from the Kilauea rift zone above.

31.1 Queen's Bath. To the left of the road, a crack contains brackish water that is part of the basal Ghyben-Herzberg lens that underlies most of the island. Road cuts expose cross sections of prehistoric pahoehoe flows.

31.5 Boundary of Hawaii Volcanoes National Park. Please don't collect specimens within the Park without special permission from the National Park Service.

32.4 Wahaula Visitor Center. Exhibits of Hawaiiana, and the Wahaula Heiau.

32.9 The lava-mantled fault scarp of Poliokeawe Pali is clearly visible inland ahead. The Poliokeawe and the lower Holei Palis (cliffs) are part of the Hilina Fault System, along which the southern edge of the island has moved downward relatively to the summit of Kilauea. The lava flows crossed by the road here are all prehistoric.

33.6 Intersection with road to Kamoamoa Picnic Area. Inland from the road a scarplet lies at the foot of the main fault scarp. Rounded hillocks near the road are tumuli, formed by up-arching of the pahoehoe flow surface.

35.5 Lae Apuki parking area. An excellent view of the sea cliff that bounds the island.

38.7 Na Ulu Sea Arches parking area. A trail leads seaward 150 feet to an excellent view of the sea cliff and sea arches. The black pahoehoe flows in this area are said by tradition to have been formed in the days of King Liloa – about 1500 A.D. Ahead and inland lava flows from Mauna Ulu during 1970 to 1973 can be seen mantling the Poliokeawe Pali.

39.9 Petroglyphs parking area. A quarter of a mile ahead the road was cut by lava flows in 1972 (Fig. 13-7). On the short walk along the road to the edge of the flow cross sections of prehistoric pahoehoe flows are seen. The 1972 flows are mostly pahoehoe, but there is also a little aa. The first low cliff is the Kealakomo Pali.

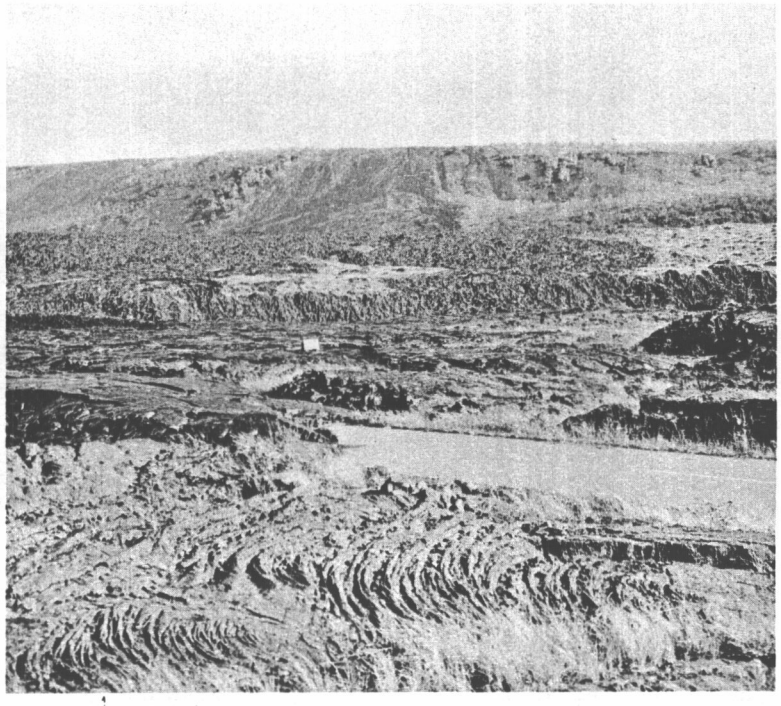


Fig. 13-7. View northwestward across the Keauhou Lava Plains (Abbott, 1973) toward the Hilina Pali and the recent lava flows from Mauna Ulu that spilled over the Pali and flowed across the plains to the sea. Chain of Craters road (foreground) is blocked by flows from Mauna Ulu. *(Photograph by Ronald Greeley, University of Santa Clara, 1974.)*

RETURN TO THE JUNCTION WITH HIGHWAY 137 AT KAIMU. PROCEED NORTH ON HIGHWAY 137.

Mileage from junction of Highways 13 and 137	
0.0	Junction of Highways 13 and 137.
0.5	Lava flow of 1750. The road continues across prehistoric flows of both pahoehoe and aa.
3.3	Parking area on right. A good view of the end of one of the 1955 lava flows, and the black sand beach formed from it. This sand is largely the result of attrition of the lava, not littoral explosion.
3.4 - 4.1	Lava flow of 1955. Beyond, the road continues across prehistoric flows.
5.7	Another small lava flow of 1955.
7.2	Opihikao. Junction with Kamaili Road.
8.2	Kaakepa, the hill on the right, is a littoral cone, formed by steam explosions where a prehistoric lava flow entered the sea.
8.6	MacKenzie State Park.
10.6	Pohoiki Junction. A road leads inland to Pahoa. Turn right and continue along Highway 137 toward Kapoho.
10.8	Isaac Hale Beach Park. Turn left toward Kapoho.
12.4	Edge of a big aa lava flow of the 1955 eruption. Inland is a good view of cones along the east rift zone of Kilauea.
13.2	The northern edge of the 1955 lava flow. Straight ahead is Puu Kukii, a cinder-and-spatter cone on the rift zone. The bigger hill just inland is Kapoho Cone, a tuff cone formed by a prehistoric hydromagmatic eruption. It contains a crater lake (Green Lake) perched a few feet above sea level because of the low permeability of the cone.
14.3	Edge of the lava flow of 1960, which destroyed most of Kapoho village (Macdonald, 1962).
14.4	Junction with Highway 132. Seaward the road leads to the Kumukahi Lighthouse, just barely spared by the lava flow. Straight ahead the road runs across the 1960 flow. The flow contains both pahoehoe and aa, much of the lava close to the point of transition from one to the other. During the eruption lava reached the surface through a fissure at the near base of Puu Kukii, heaving up the old ground surface about 50 feet. Turn left on Highway 132.
15.0	Site of former Kapoho village. To the right, Puu Laimana (Lyman Hill) is the principal cone of the 1960 eruption. It contains a larger proportion of ash than most Hawaiian cones, because the rising lava encountered ground water only about 80 feet below the surface, resulting in steam explosions accompanying the normal lava fountains. The red hill on the left of the road is a prehistoric cinder cone built against the side of the Kapoho tuff cone. Beyond Kapoho the road continues across prehistoric lavas.
16.5	Edge of an aa lava flow of the 1955 eruption.
17.2	Spatter cones at vents of the 1955 eruption.
19.4	Junction with road to Pohoiki.
19.6	Lava Trees State Park. The 1790 lava flow buried a forest of ohia trees, then drained away, leaving tree molds standing above the lava surface.
20.1	The road crosses the forested 1840 lava flow.
22.1	Junction with Highway 13.

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